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The Morphology And Contractile Function Of Skeletal Muscle In Aged Humans

Charles Leslie Rice

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THE MORPHOLOGY AND CONTRACTILE FUNCTION OF SKELETAL MUSCLE IN AGED HUMANS

by

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of the requirements for the degree of
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ABSTRACT

Muscle strength and morphology were investigated in four studies in elderly men and women between the ages of 62 and 102 years. The purposes were to: 1) measure the voluntary strength in several limb muscle groups from an 'older' elderly population, 2) measure and compare the amount of muscle and non-muscle tissue (NMT) in the arms and legs of older (65 + years of age) and younger (25 to 38 years of age) males using computed tomography (CT) scans, 3) compare the CT results with measures of anthropometry in the same two groups of males, and 4) measure the electrically evoked and voluntary strength parameters in an elderly group (65 to 78 years of age) following a six month strength training program of the elbow extensors.

In the first study, the voluntary strength of several limb muscle groups was measured in 118 subjects using a modified sphygmomanometer. The device permitted a simple, adaptable means of quickly testing a wide variety of muscle groups. Multiple regression analysis identified that age was the foremost explanatory variable to account for the decline in strength with age (2% to 3% per year).

In the second and third studies five nearly equidistant (CT) scans of the leg and five of the arm were taken on 7 younger (25 to 38 y) and 13 older (65 to 90 y) males.

Corresponding girth and skinfold measures were also made. From the CT scans total limb area, muscle plus bone area, skin and subcutaneous area, bone area and particular muscle group areas were measured. In addition, the amount of non-muscle tissue (NMT) within a muscle group was quantified. Corresponding volumes were also estimated for the CT and anthropometry measures. Muscles of aged subjects were smaller than those of the young and contained a significantly greater proportion of NMT, particularly in the plantar flexors. Anthropometric prediction equations were developed, but predictability was not strong for individual muscle groups in the aged men.

In the fourth study, 13 elderly subjects aged 65 to 78 years were involved in a six month elbow extensor strength training program and 8 subjects served as an age and activity matched control group. Electrically evoked as well as voluntary strength measures were made at 0, 12, and 24 weeks in the experimental group. The subjects improved their voluntary strength approximately 20% in 24 weeks. Evoked tetanic torque was also increased. Temporal twitch parameters were slowed with training. The results suggest that, in response to strength training, some of the alterations in muscle properties may be related to muscle size and connective tissue changes, and not only to central neural changes.

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CHAPTER ONE

GENERAL INTRODUCTION AND BACKGROUND

To most people, the term human research on ageing probably implies investigations associated with dementia and other disease states which one usually believes to be expected accompaniments to a long life. While these observations are valid, and without a doubt further research is needed in these areas, there are other aspects of research on ageing not usually associated with a disease condition per se. The overall process of ageing has been described as being progressive and deleterious (i.e., reduced function) (Strehler, 1982), and it is this aspect of the research in ageing - the natural progressive decline in functional physical abilities - which is the concern of this thesis.

It is a common observation that older individuals move slower, are weaker, and have reduced physical endurance compared with younger adults. Central to these observations is movement. To produce purposeful movement, the generation of force is required through muscle contraction. Movement can also be thought of as a primary determinant of independence, that is, the ability to live without requiring institutionalized care, and since the population is ageing, this issue is becoming an important concern in society

(Vandervoort et al., 1986). It is surprising, however, that there is a relative dearth of research which has investigated the relationship between skeletal muscle function and ageing (Larsson, 1982; Green, 1986).

1.1 Muscle, Ageing, and Physical Activity

The intimate structural and functional relationships between muscle and nerve tissue have suggested to investigators that changes in muscle histophysiology are secondary to, or expressions of alterations in the neural portion of the motor unit (Campbell, 1973; Larsson, 1978; Lexell et al. 1988). This concept is applicable to both ageing muscle and stress induced muscle changes. While this is probably a reasonable hypothesis, it should not be over-emphasized to the exclusion of other ageing/activity changes that may be associated with the muscle portion of the motor unit and its associated structural supporting tissues. These aspects have been recently emphasized and reviewed (Vandervoort et al., 1986; Jones and Rutherford, 1987; Sale, 1987; Enoka, 1988).

Usually the age-related loss of strength has been described as linear, beginning from a peak at about age 30 years (Skinner et al., 1982). Other evidence suggests that the loss in neuromuscular function is curvilinear from age 30 (Drevor et al., 1985). More recently, Lexell, et al. (1988) have shown that the loss of muscle fibre number and atrophy in muscle fibre size with age follows a quadratic relationship, and that between 24 and 80 years of age the reduction is about 40% in each of these measures. Other researchers have suggested that the number of limb motoneurones (Tomlinson and Irving, 1977) and voluntary strength (Vandervoort and McComas, 1986) remain relatively constant until about 60 years of age, and then demonstrate a relatively steep linear decline. The loss in maximum voluntary strength in leg muscles was from 20% at age 75 to 50% by age 90 (Vandervoort and McComas, 1986). Whatever the relationship, it seems that there is a relatively modest decline in function until beyond 75 years of age. Since many people possess adequate strength in their eighth to tenth decade of life, it appears that functionally the system has a relatively large reserve capacity that is gradually eroded with old age (Vandervoort et al., 1986). A small change in maximum muscle function in aged individuals can therefore translate into a relatively large increase in sub-maximal working capacity.

Classically, skeletal muscle tissue is described as possessing four special properties: irritability, contractibility, distensibility, and elasticity. Adaptability should also be included in this list. Studies in both young and older adults have shown that muscle strength can be substantially improved with increased useage, and lost with disuse (Skinner et al., 1982; Goldberg et al., 1975; MacDougall, 1986; Sale, 1987; Enoka, 1988). However, few investigations concerning the response of muscle in the elderly (>65 years) to strength training have been performed (see review by Vandervoort et al., 1986).

The question often asked in human research concerned with ageing is: does ageing result in reduced activity thereby mediating functional and anatomical muscle deficits, or does reduced activity, because of the self-perception that at age 65 one must reduce physical activity, cause much of the age-related losses? Since long-term longitudinal studies on ageing are not usually feasible, this issue becomes one of the inherent problems with human ageing research. Researchers are therefore resigned to cross-sectional descriptive studies, correlative models, or intervention designs, such as training, to address this question.

1.2 Thesis Outline

The overall purpose of this thesis is to investigate selected aspects of muscle structure and function in primarily an aged population (65 - 90 years). To this end, the thesis was divided into four subsequent chapters (papers), each utilizing one of the study designs outlined above, to address a particular deficit in the existing research literature. Each chapter provides its own pertinent background and literature review, and although the results of one do not necessarily support the rationale for the next, they are arranged in a logical sequence.

The first study (Chapter Two) is descriptive and was designed to provide measures of easily obtainable voluntary strength from several limb muscle groups in a relatively large number of 'older' elderly individuals.

One of the facets of ageing that has not been examined in any systematic detail is the composition of limb muscles in aged individuals compared with younger adults. Computed tomography techniques (CT scans) were used in the third chapter and combined with surface anthropometry in the fourth chapter to provide quantitative information about muscle composition changes with age and the relationship of these results to surface measures. There are some common methods to each study, but they are only described in detail once in the fourth chapter and referred to in the fifth.

The fourth study (Chapter Five) describes a six month strength training study in aged subjects. The technique of electrically evoked contractile properties was used to separate muscle from neural effects.

CHAPTER TWO

THE MEASUREMENT OF VOLUNTARY STRENGTH IN AN AGED POPULATION

2.1 INTRODUCTION

Muscle strength data, from various upper and lower limb muscle groups, is quite limited for an elderly population over 65 years of age. Muscle, or muscle groups involved with knee extension, plantar flexion, dorsiflexion, handgrip, and elbow flexion have been studied most frequently (Bosco and Komi, 1980; Flatten and Rice, 1982; Pearson, et al., 1985b; Vandervoort, et al., 1986). The age interval in many of these studies has been limited to the 7th and early 8th decades, and the total number of either male or female subjects studied is usually fewer than 30. In order to study a variety of limb muscle groups for a large number (> 100) of elderly subjects in their 8th and 9th decades, many of whom are restricted to nursing homes, a simple, adaptable, portable strength measuring device was required. The modified sphygmomanometer (MS), described and validated by Helewa, et al., (1981) for testing muscle strength in arthritic patients, seemed to be an appropriate device for this task.

The main purposes of this study were: to measure and establish descriptive data for the strengths of a variety of upper and lower limb muscle groups in an aged population; and to evaluate the modified sphygmomanometer as a strength testing device in this population. It has been previously used only as a qualitative strength monitoring device. We have attempted to improve the qualitative aspect by comparing it to results using other strength devices in studies of the aged and providing strength categories from which differences and changes can be assessed.

2.2 METHODS

A total of 118 individuals (37 males and 81 females) between the ages of 62 and 102 years participated in the study. The subjects were consenting volunteers recruited from the London and area community. Almost one-half (n = 55) of the participants resided in nursing, or other care facilities and were considered dependent dwellers, whereas the others (n = 63) were capable of living independently in private homes or apartments. All subjects were mentally capable of understanding and performing the tests and were ambulatory with, or without aids. The study was approved by the University Standing Committee on Human Research.

Height, weight, four skinfold measurements (biceps, triceps, subscapular, suprailiac), and strength measurements were recorded for all individuals. The skinfold measurements were taken on the right side of the body using Harpenden calipers. Strength testing was performed using the modified sphygmomanometer (MS), consisting of a folded bladder of a sphygmomanometer incorporated into a sewn bag as described by Helewa, et al., (1981) and Giles (1984). The MS is inflated to a baseline reading (see below, page 9) on the anaeroid scale (mm Hg). The tester places the bag on a limb segment and the subject is either asked to resist movement of the corresponding joint as the tester applies force, or to attempt to induce movement by exerting force against the tester. In either case, a "break" in movement, or a tremor indicates a maximal isometric contraction of the particular muscle group and the tester records the force as a pressure (mm Hg). An additional modification was to secure the bag to a piece of plywood (15 x 20 cm) by means of a wide cloth strap (10 cm). The attachment to the board allowed for a more uniform and stable pressure to be applied by the tester. All calibration and baseline inflation values included the attached board, with the exception of handgrip measurements for which the board was removed and the MS readjusted to baseline (see below). A Stoelting dynamometer was also used for handgrip testing.

The modified sphygmomanometer was calibrated by placing known weights on the bag. Combinations of weights were used in increments varying from 1 kg to 5 kg, up to a total of 30 kg. The bag was inflated to 20 mm Hg for a baseline measurement corresponding to zero weight applied. An equation was derived so that the pressures recorded in mm Hg could be converted into kg of force. A linear relationship ($r = 0.994$) was found between the anaeroid measurement and the known weights in which 1 kg corresponded to approximately 9 mm Hg [y (kg) = $-3.18 + 0.114(x)$ mm Hg]. Figure 1A illustrates the calibration curve from which the equation was derived. Helewa (1981) indicated that calibration of the MS was best fit by a polynomial equation. In this study, a polynomial equation also provided a slightly better fit ($r = 0.999$) (Fig. 1B), but since it is not as easy to derive in a practical situation, the equation in figure 1A was used. In addition, the difference between the two for determining a kilogram of force was minimal (<5%), especially for the interval of most measurements (100 mmHg to 250 mmHg). A mercury manometer was used to ensure the accuracy of the anaeroid scale. Before testing, the MS was inflated to 100 mmHg to remove any folds in the bladder and then deflated to a baseline of 20 mmHg. The effective measurement range was between 20 mmHg (0 kg) and 300 mm Hg (31 kg). Measurements beyond 300 mmHg could not be assessed and were discarded. Although the correct unit of force is a newton, most related studies report forces in kg, and, as well, the meaningfulness of a newton as a measure of strength may not be widely appreciated. The conversion is 1 kg is equal to 9.806 newtons (N).

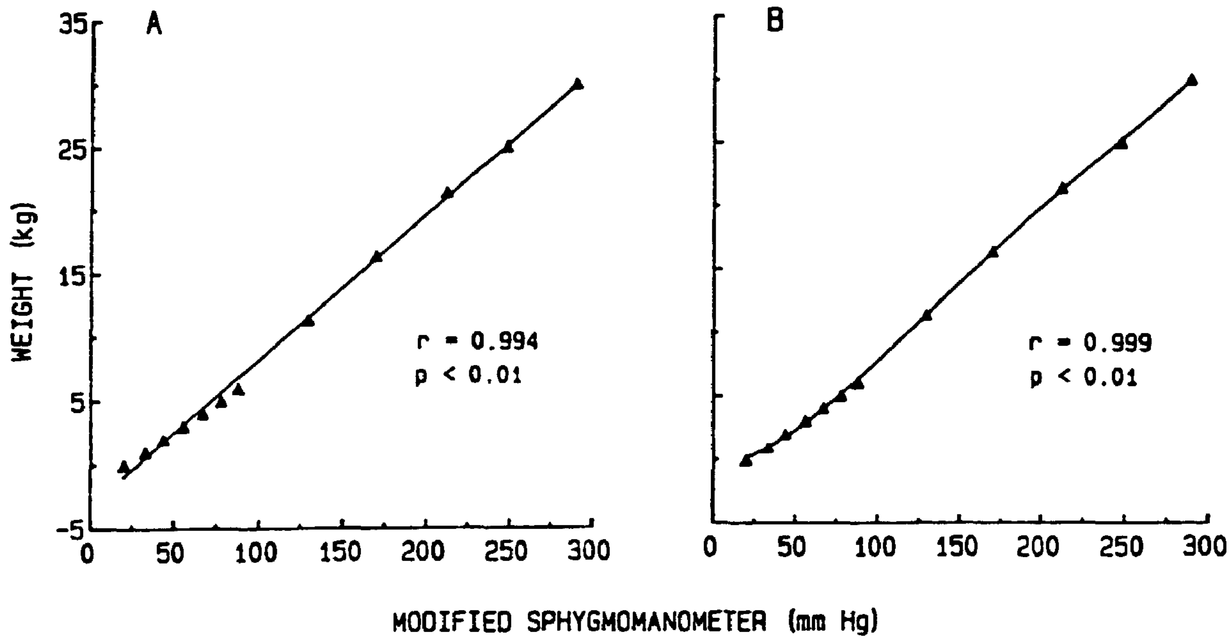

Fig. 1 Comparison of calibration curves of the modified sphygmomanometer. A linear regression fit is illustrated in A with the equation: $y(kg) = -3.18 + 0.114(x)$ mmHg.

A polynomial fit is illustrated in B with the equation:

$y(kg) = -0.6 + 0.02(x) + 9.4x10^{-3}(x^2) - 3.5x10^{-6}(x^3) + 4.4x10^{-9}(x^4)$.

2.2.1 Strength Testing Procedures

Muscle groups acting across the shoulder (glenohumeral), elbow, wrist/hand, hip, knee, and ankle joints were tested. Movements governed by the pertinent muscle groups included shoulder abduction and forward flexion, elbow extension and flexion, hip extension and flexion, knee extension, dorsiflexion, plantar flexion, and handgrip. The muscle groups of the dominant side were chosen for measurement unless there was a neuromuscular or orthopaedic limitation, in which case the opposite limb, or no measurement was taken of that particular movement. Measurement of handgrip strength included both the MS and the handgrip dynamometer.

Details and descriptions for administering the strength tests for shoulder abduction and flexion, elbow flexion, and knee extension can be found in Helewa (1986), and for handgrip using the MS and dynamometer in Giles (1984). Modifications to these methods or additional tests not described in the above articles include: elbow and hip extension, dorsiflexion and plantar flexion. For elbow extension the subject was seated with the arm in the dependant position, elbow flexed to 90° and forearm supinated. The MS was placed on the dorsal surface of the forearm, proximal to the styloid process. The subject attempted to maintain the elbow position as the tester applied upward force. Hip extension was tested with the subject standing on one leg, leaning forward on a wall or rail. The free lower limb was extended to 45° at the hip with the knee at 180° (extension). The MS was positioned over the posterior surface of the thigh, proximal to the knee joint. The subject resisted hip movement as the tester applied forward force. Dorsiflexion and plantar flexion measurements were made with the subject seated on a sturdy table with legs hanging freely. Hands were placed behind for support while keeping the hip at 60° (flexion) and the knee at 90°. For dorsiflexion, the MS was placed on the dorsum of the foot proximal to the phalanges with the ankle held in full dorsiflexion and resisting the downward force applied by the tester. For plantar flexion the ankle was in the neutral position and the MS held under the ball of the foot by the tester. The subject actively plantar flexed against the resistance of the tester. The subject was encouraged to resist the temptation to push down with the whole lower limb.

The mean of two measurements of peak tension maintained for 3 to 5 seconds was taken for each muscle group, and a third measurement taken only if the first two varied by more than 5 percent. The order of testing for all subjects followed the order given in Table 2 (page 16). Total testing time for one subject was between 10 and 15 minutes.

2.2.2 Statistical Analyses

The pressure measurements (mmHg) were converted to kg of force using the calibration regression equation. Means and SD's were calculated separately for men and women for all strength tests, as well as relative strength values based on individual body weight (kg/kg). A Student's t-test was used to compare differences in all physical measurements between men and women. A factor, or cluster analysis was used to determine if certain upper and lower limb strength measurements could be identified that would provide the best indication of overall limb strength. Finally, relationships between these four representative strength measurements, identified from the factor analysis, and the anthropometric indices were derived using a Pearson product-moment correlation analysis. A subsequent forward step-wise multiple regression analysis was used to examine the association between the dependent strength measures and the independent, or explanatory anthropometric variables. This analysis computes an F-statistic for each explanatory variable with the other variables held constant similar to an analysis of covariance (Nie, et al., 1975). It also assesses the increment variance with each variable and the total variance explained.

2.3 RESULTS

There were no significant differences between the ages of the men and women, but the males were significantly ($p \leq 0.05$) taller and heavier than females. Females had a significantly higher sum of four skinfolds and significantly larger triceps skinfold than the males. A body mass, or Quetelet index, calculated as the ratio of weight (kg) to height (m^2) and often used as a measure of fatness, was not different between the sexes (Table 1).

The absolute and relative strength measurements for both males and females are summarized in Table 2. In each group the total number of measurements for each muscle is given. The maximum possible is 37 for males and 81 for females. A number of tests do not include the full complement of subjects due to physical limitations or exceeding the limit of the MS (see Methods). Parentheses in Table 2 indicate the number of measurements which exceeded the limit of the device. The smaller number of dynamometer measurements for females was due to initially not using the dynamometer until it was realized that some individuals were able to overcome the limit of the MS. With the exception of the MS grip strength, all absolute strength measurements in men were significantly greater ($p \leq 0.05$) than the women. When body weight was taken into account, however, all measurements except the handgrip

TABLE 1. Subject Characteristics

	Men (n=37)	Women (n=81)
Age (y)	79.3 ± 7.2 (70-102)	77.1 ± 5.9 (62-92)
Height (cm)	169.1 ± 7.6* (154.6-185.4)	157.4 ± 7.7 132.6-173.0)
Weight (kg)	71.7 ± 10.2* (52.6-92.5)	60.4 ± 11.0 (39.1-99.1)
Quetelet($kg.m^{-2}$) Index	25.3 ± 4.0 (20.0-31.3)	24.6 ± 4.8 (17.5-32.8)
Sum of 4 Skinfolds (mm)	51.8 ± 19.2* (20.0-101.0)	64.1 ± 24.8 (22.7-112.4)
Triceps Skinfolds (mm)	11.8 ± 5.8* (4.0-26.2)	20.1 ± 7.6 (6.5-37.1)

Values are means ± S.D. (Interval)

* indicates significant difference ($p \leq 0.05$) between men and women

TABLE 2. Absolute and Relative Strength Measurements

Muscle Groups	MALES Strength (kg)	MALES Strength/ body weight (kg/kg)	MALES n	FEMALES Strength (kg)	FEMALES Strength/ body weight (kg/kg)	FEMALES n
Shoulder Abductors	12.4±5.0*	0.17±0.07	37	9.3±3.3	0.15±0.05	81
Shoulder Flexors	12.7±5.0*	0.17±0.07	37	9.3±3.4	0.14±0.05	81
Elbow Extensors	14.9±4.6*	0.20±0.06	37	11.2±3.3	0.19±0.06	81
Elbow Flexors	15.2±5.1*	0.21±0.07	37	10.9±3.9	0.18±0.06	81
Hip Extensors	14.4±5.8*	0.19±0.08	31 (2)	11.6±4.0	0.19±0.06	69 (1)
Hip Flexors	16.2±6.7*	0.23±0.09	31 (2)	10.8±3.3	0.18±0.06	74 (1)
Knee Extensors	19.1±5.7*	0.27±0.09	31 (5)	16.7±4.8	0.28±0.08	77 (2)
Dorsiflexors	15.1±4.5*	0.21±0.07	37	12.6±4.1	0.21±0.06	79
MS Grip	23.2±4.4	0.33±0.08	20 (17)	20.1±5.7	0.31±0.09	74 (7)
Dynamometer Grip	30.8±6.6*	0.43±0.1*	37	21.6±6.1	0.36±0.08	64

Values are means ± SD 1 kg = 9.806 newtons. MS is modified sphygmomanometer and n is number of subjects. Parentheses indicate the number of measurements which exceeded the upper limit of the MS.

* indicates significant difference ($p \leq 0.05$) between males and females for absolute or relative strength measurements.

dynamometer were not significantly different between the sexes.

The results of the factor analysis identified four measurements, two upper limb (elbow flexion and grip) and two lower limb (knee extension and dorsiflexion), that could be used as the best indicators of overall limb strength using the modified sphygmomanometer. A correlation matrix is presented in Table 3 to illustrate the simple correlations between these four strength measurements and anthropometric variables. Significant negative correlations ($r = -0.33$ to -0.65) between strength and age were obtained for both men and women. Age was also negatively correlated with weight for both sexes and with height in males. Most of the strength measurements were significantly and positively correlated with height in both sexes and with weight in females. The multiple regression analysis identified that, for males, age was the only significant explanatory variable of strength accounting for 16% (knee extension) to 40% (grip) of the explained variance (R^2). For the females, age, and in three cases weight, were the significant explanatory variables. The explained variance ranged from 11%, with only age for grip, to 21%, with age and weight for dorsiflexion.

Four regression equations for each sex are presented in figures 2 and 3. Age is the only factor needed for the

TABLE 3. (A) Matrix of Simple Correlations (r) Among Variables for Females

	Dorsiflexors	Knee Extensors	MS Grip	Elbow Flexors	Sum of Skinfolds	Weight	Height
Age (y)	-0.33	-0.34	-0.33	-0.34	-0.40	-0.23	-0.08
Height (cm)	0.25	0.12	0.23	0.30	-0.05	0.21	
Weight (kg)	0.40	0.29	0.23	0.34	0.72		
Sum of Skinfolds (mm)	0.33	0.28	0.28	0.31			

Critical level of r is 0.23 for $p \leq 0.05$ with n=74.

(B) Matrix of Simple Correlations (r) Among Variables for Males

	Dorsiflexors	Knee Extensors	MS Grip	Elbow Flexors	Sum of Skinfolds	Weight	Height
Age (y)	-0.53	-0.40	-0.63	-0.65	-0.18	-0.35	-0.36
Height (cm)	0.40	0.28	0.53	0.41	-0.18	0.26	
Weight (kg)	0.26	0.16	0.08	0.39	0.69		
Sum of Skinfolds (mm)	0.00	0.03	-0.02	0.13			

Critical level of r is 0.33 for $p \leq 0.05$ with n=31.

MS is modified sphygmomanometer

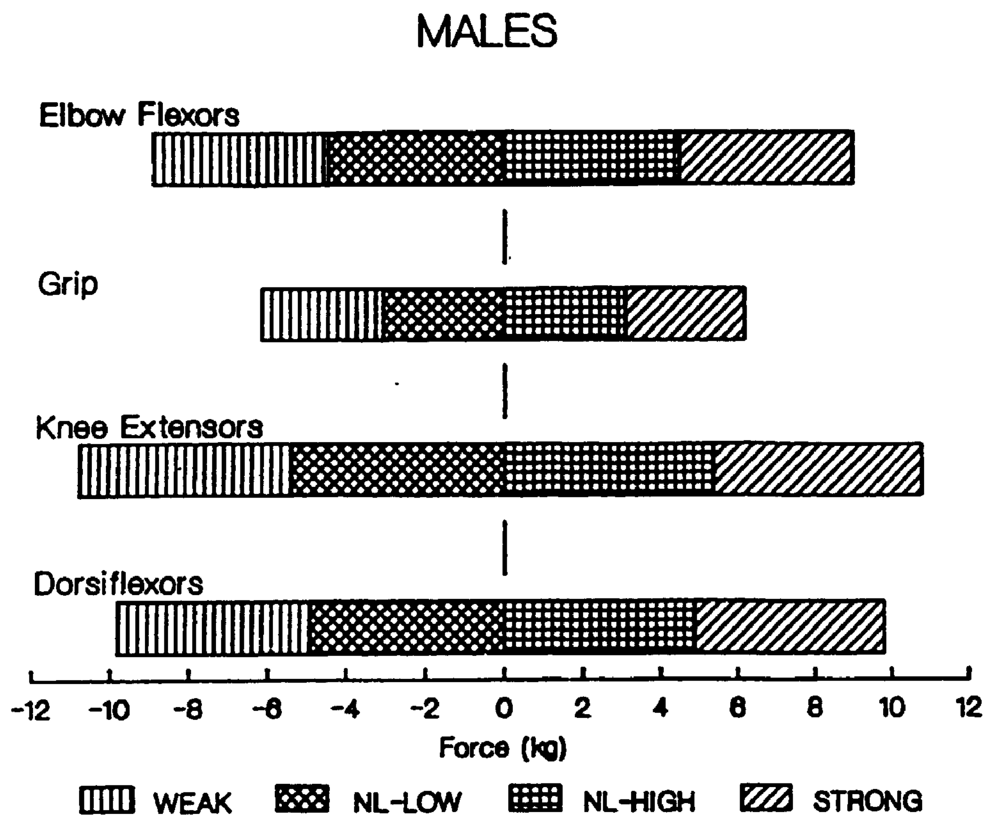

Fig. 2 Predicted Strength of:

Elbow Flexors (kg) = 58.8 - 0.55 (age,y) R = 0.65
SEE = ± 4.5 kg

MS Grip (kg) = 57.1 - 0.42 (age,y) R = 0.63
SEE = ± 3.1 kg

Knee Extensors (kg) = 42.7 - 0.29 (age,y) R = 0.40
SEE = ± 5.4 kg

Dorsiflexors (kg) = 47.5 - 0.40 (age,y) R = 0.53
SEE = ± 4.9 kg

To determine strength for a particular age of male between 70 and 102 years of age; compare predicted value using equation to the actual strength measure using the modified sphygmomanometer. If actual strength is greater than predicted; within 1 SEE then strength is NL to high; if greater than 1 SEE then subject is in strong category. Negative categories are similarly used if actual strength is less than predicted. Note: these scales may be slightly skewed towards a weaker population (see text). A broader interpretation should be given for grip strength.

SEE = standard error of estimate. NL to high = Normal to high strength; NL to low = Normal to low strength. 1 kg = 9.806 newtons. MS is modified sphygmomanometer.

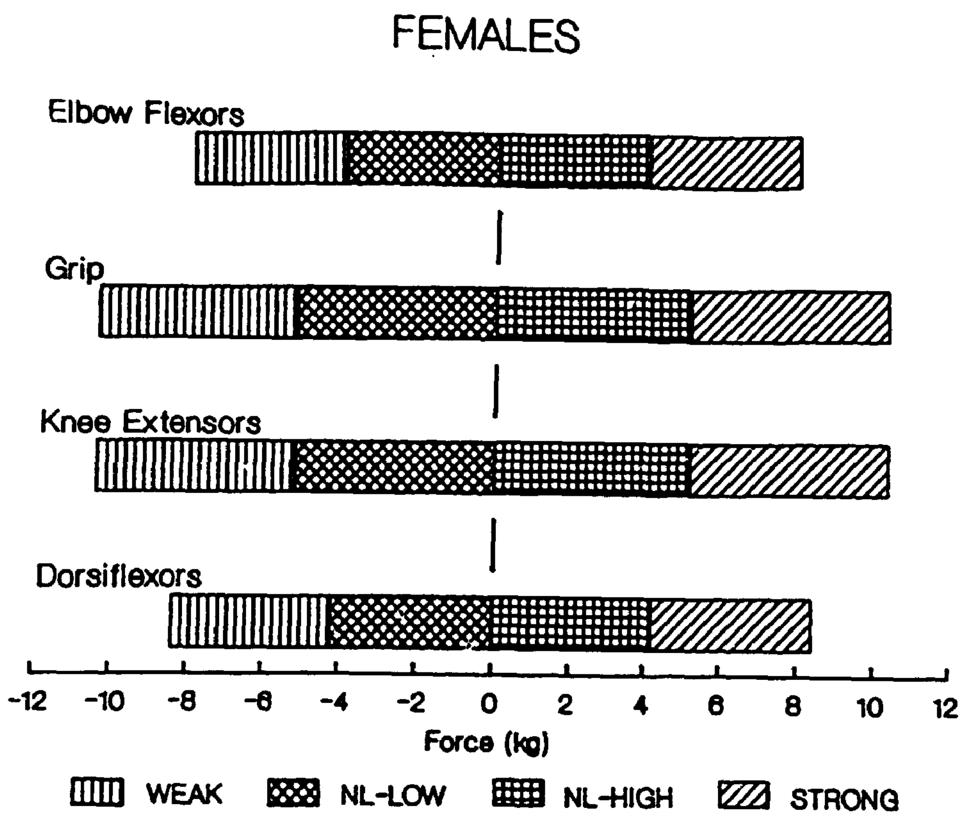

Fig. 3 Predicted Strength of:

Elbow Flexors (kg) = 19.8 + 0.17 (weight,kg) - 0.20 (age,y) R = 0.44 SEE = ± 4.0 kg

MS Grip (kg) = 40.8 - 0.27 (age,y) R = 0.33 SEE = ± 5.2 kg

Knee Extensors (kg) = 32.2 + 0.11 (weight,kg) - 0.28 (age,y) R = 0.41 SEE = ± 5 ? kg

Dorsiflexors (kg) = 18.9 + 0.15 (weight,kg) - 0.19 (age,y) R = 0.46 SEE = ± 4.2 kg

To determine strength for particular age or age and weight of female between 62 and 92 years of age; compare predicted value using equation to actual strength measure using modified sphygmomanometer. If actual strength value is greater than predicted; within 1 SEE then strength is NL to high; if greater than 1 SEE then subject is in strong category. Negative categories are similarly used if actual strength is less than predicted. Note: these scales may be slightly skewed towards a weaker population (see text).

SEE = standard error of estimate, NL to high = Normal to high strength; NL to low = Normal to low strength. 1 kg = 9.806 newtons. MS is modified sphygmomanometer.

equations, except for three equations for females which require both age and weight factors. For a qualitative comparison within an aged population the predicted and actual measured scores can be compared and an individuals' strength categorized as normal-high, strong, normal-low, or weak.

2.4 DISCUSSION

The usefulness and validity of the modified sphygmomanometer to measure muscle strength have been reported previously, but the assessments were limited to populations of weaker subjects afflicted with movement related pathologies such as rheumatoid arthritis (Giles, 1984; Helewa et al., 1981; Helewa, 1986). Reduced muscle strength is also associated with normal ageing (Vandervoort and McComas, 1986), and therefore this apparatus was appropriate for field testing a large sample of aged subjects. Testing a variety of subjects, including large ranges in age and degree of physical abilities, and the testing of various muscle groups, however, identified certain limitations of the MS for accurate strength assessment.

2.4.1 Testing Apparatus and Methods

Studies in older individuals that have reported strength values for knee extensors, dorsiflexors, and elbow flexors all used more elaborate isometric, or isokinetic dynamometers in which limb segments could be well stabilized to allow the subject to exert maximal efforts. The modified sphygmomanometer, on the other hand, partially relies on subjects stabilizing themselves while attempting to exert maximal force of a particular muscle group. The net result of this additional stabilizing effort is a reduction in the amount of applied force by the desired muscle group. This limitation is especially pertinent for the large, powerful knee extensor muscle group.

The alternate technique described in this study to measure hip extension strength was not entirely satisfactory and the results may not accurately reflect maximal capacities (see subsequent discussion). The side lying technique for hip extension suggested by Helewa (1986) was also not suitable due to breathing difficulties that often ensue in the recumbent position of aged individuals. For this reason measurements of knee flexion strength were not attempted.

An important limitation of the MS is that for some of the measurements the younger (less than 75 years), and more vigorous subjects were able to overcome the anaeroid scale. This limitation was also reported by Helewa (1986). It should be appreciated that, since stronger subjects who overcame the limit of the MS were eliminated from the results for that muscle group, the remaining data can not be considered normative, but skewed towards a weaker aged population. It is likely that this would only have a major influence on male grip results, since the number exceeding the limit for the other muscle groups was minimal (Table 2).

The apparatus and technique employed in this study was not satisfactory for testing plantar flexion strength. The short lever arm of the foot combined with the potential for large forces to be exerted (McDonagh et al., 1984; Pearson et al., 1985b; Vandervoort and McComas, 1986) did not permit an accurate assessment of plantar flexion strength using the present method. Plantar flexion results are therefore not included in Table 2 since they were approximately five times lower than the values reported in the above mentioned studies and, in view of the limitations with this measurement, would not be expected to provide a good reflection of muscle strength. Helewa (1986) stated that the device was not suitable for testing muscles acting across the ankle joint, however, the findings in this study would substantiate this precaution in so far as the ankle plantar flexors are concerned, but not the dorsiflexors. The measurement of dorsiflexor strength using the method described in this study, proved to be very satisfactory in this population. The difference for this ankle group is most likely due to their relative weakness compared to the plantar flexors (Vandervoort and McComas, 1986), and the more suitable testing position.

2.4.2 Strength Characteristics

The subjects in this study were physically representative of this age group (Burr and Philips, 1984; Chumlea et al., 1986; Fulop et al., 1985; Pearson et al., 1985a). Available isometric strength results from other studies in an aged population are very limited, but have included handgrip, knee extension, dorsiflexion, plantar flexion and elbow flexion, and therefore comparisons can only be discussed with respect to these muscle groups.

The usefulness of the MS is to provide primarily a qualitative indication of muscle strength, and, although the results for several muscle groups are similar to those reported using other devices (see below), the limitations previously discussed should be appreciated when making these comparisons. Only grip strength measures using the dynamometer can be directly compared to other studies and the results from this study are very similar to values recently reported by Mathiowetz, et al. (1985) and Rikili and Busch (1986) for males and females over 65 years of age.

The quartile scales in figures 2 and 3 are convenient for categorizing strength and may also prove to be expedient for grouping strength changes in the aged associated with disuse, increased activity, or rehabilitation. The scales are based on the number of subjects who did not exceed the device. This is not considered to have a major impact since, except for the male MS grip results, only a small percentage (<10%) of subjects, based on combined male and female knee extensors and female MS grip, exceeded the limit. The male MS grip scale may still be qualitatively useful as long as the user is aware that it is based on a weaker population. Until an MS with an expanded scale is available and tested, the standard handgrip dynamometer would provide a better measure of strength in males. In females, however, it appears that the MS provides a good indication of grip strength with a correlation between the two devices of r = 0.81 (n = 64).

Vandervoort and McComas (1986) reported dorsiflexor forces for both elderly males and females that were very comparable to the values found in this study. Aniansson, et al. (1986), using a custom built arm dynamometer reported only slightly higher average elbow flexor values (21.5 kg compared to 15.2 kg in this study) in their study of men of an average age of 77 years. Elbow flexor strengths have also been reported by Pearson, et al (1985b) for relatively younger males and females and their results were nearly double for males and about 40 percent greater for females than the results in this study. McDonagh, et al. (1984) also found similar results as Pearson, et al. (1985b) for males. The greater age of the subjects (79 years vs. 71 years for the two aforementioned studies) as well as the different measurement devices employed would probably account for the lower values in the present study. In fact, it was determined in this study from the slopes of the regression equation that there is a mean (males and females combined) lcss of 3% per year in elbow flexor strength due to age.

Knee extensor strengths have been reported in a number of studies for both men and women over 65 years of age (Aniansson et al., 1986; Bassey and Harris, 1987; Murray et al., 1980; Murray et al., 1985; Young et al., 1984; Young et al., 1985). These studies report values of between approximately 20 and 50 kg of isometric force; the lowest values for older females up to age 86 years, and the highest values for younger males between 65 and 70 years. The mean values reported in this study for either sex are nearly 50 percent lower than in these other studies. Differences in testing methods and the average older age of the subjects in this study would probably account for smaller values. Aniansson, et al. (1986) reported a decrease of approximately 25% in knee extensor forces in males between 70 and 77 years of age. The present results show an average loss for both sexes of nearly 2% per year.

The multiple regression analyses have demonstrated that in women, age, followed by weight, were the significant independent variables which explained most of the strength variance. In men, however, weight was not significant, leaving age as the only significant explanatory variable of strength. This effect for males could be due to either a stronger negative correlation between age and weight (r = -0.35) than found for women (r = -0.23), or an overall greater loss of strength with age for men as shown by the slopes of the regression equations (Figs. 2 and 3).

The decline in weight with increasing age is of a similar order for females (r = -0.29) as that reported by Pearson, et al. (1985b). When comparing males and females, or individuals within the same sex, strength is often normalized by relating it to body weight(Bishop et al., 1987; Komi, 1984). Body weight is a simple anthropometric measurement that may reflect overall muscle cross-sectional area, and therefore differences in actualized strength (Edwards et al., 1984). In this study body weight was an important factor for making comparisons between males and females since strength differences were equalized between the sexes when normalized for body weight (Table 2). It appears, however, that within either sex of this population age may be the most significant variable to account for strength differences with weight being of lesser importance (see equations in Figs. 2 and 3). The degree of strength decline for the population in this study, determined across the four strength measurements, was 1.5% to 2% per year for females and 1.5% - 3.5% per year for males. In similar aged populations, Pearson, et al. (1985b) reported declines of 1% to 2% per year for calf and biceps brachii strength, and MacLennan, et al. (1980) reported a 2% per year decline in handgrip strength.

The significant decline of height in males with increasing age (Table 3B) was also reported by Pearson, et al. (1985b). They suggested an age-related kyphosis and it therefore might be inappropriate to include height in a strength analysis in an aged population.

In summary, the results of this study have provided upper and lower limb strength data for aged subjects using an apparatus not previously validated for this population. By applying the modified sphygmomanometer to a variety of upper and lower limb muscle groups in individuals between 62 and 102 years of age, limitations and advantages of the testing device have been identified. The method of testing and the MS itself are not suitable for measuring muscle strength of certain muscle groups in relatively younger, vigorous subjects, and for plantar flexors in all subjects. In view of the number of subjects who exceeded the device, the results for male grip should be interpreted cautiously since they represent a slightly weaker population. The resistance applied by the tester, or the device, or both are overcome by vigorous subjects, and the lack of adequate body stabilization for these subjects detracts from providing a recordable maximal effort. If these restrictions are kept in mind, the modified sphygmomanometer is an acceptable device to obtain primarily a qualitative measure of strength particulary for elbow flexors, handgrip, knee extensors, and dorsiflexors in an 'older' elderly population. The multiple regression analyses identified age as the main determinant of strength within either sex in this population. The equations and scales presented in figures 2 and 3 may allow the modified sphygmomanometer to be especially useful as a means of screening and identifying aged individuals with significantly weakened limb strength. This may also be important for monitoring progress during rehabilitative therapy.

CHAPTER THREE

ARM AND LEG COMPOSITION DETERMINED BY COMPUTED TOMOGRAPHY IN YOUNG AND AGED MEN

3.1 INTRODUCTION

When muscle forces are compared between individuals it is necessary to have a measure of the amount of muscle associated with a movement. The inability to accurately quantify the amount of functional muscle *in vivo* is a major difficulty in human research. This limitation is of particular concern when strength capacities of widely different groups, such as athletes and non-athletes, or normal individuals and patients with neuromuscular disorders, are compared (Haggmark et al., 1978; Grindrod et al., 1983; Jones et al., 1983; Maughan et al., 1986). Normal aged, in comparison with normal younger individuals, demonstrate significantly reduced limb strength capacities (Vandervoort et al., 1986), and to date little research has been directed towards quantifying changes in limb muscle morphology which may explain age-related strength differences. Most studies have suggested that the reduced muscle capacity in old age is partly due to generalized muscle atrophy and replacement of muscle with adipose and areolar connective tissue (Larsson, 1982; Murray et al., 1985; Young et al., 1985; Vandervoort and McComas, 1986), but none have quantified these differences *in vivo*.

Early studies were limited by the imaging techniques and the ability to quantify findings (Inglemark and Gustafsson, 1957; Noble et al., 1956; Helander, 1959). More recent imaging studies using ultrasound or computed tomography (CT) techniques to examine limb morphology have limited measurements to one scan, usually at the point of largest girth (Maughan, 1984) and only a few have investigated aged subjects (Bulcke et al., 1979; Borkan et al., 1983; Young et al., 1985; Vandervoort and McComas 1986). Two CT studies that have examined skeletal muscle in young and aged subjects reported that in the older subjects there was a greater preponderance of fat located between the limb muscles, but did not note differences of fat deposition within the boundaries of the muscles (Bulcke et al., 1979; Borkan et al., 1983). One CT study did report a reduction with age in average CT number (Hounsfield units HU) and muscle cross-sectional area (CSA) in the psoas major and sacrospinalis muscle groups in individuals aged 20 to 89 years (Imamura et al., 1983). The reduced CT number implies that the muscle tissue has become less dense with age, presumably due to infiltration by non-muscle tissue. One very recent study has used multiple scans obtained by nuclear magnetic resonance imaging in six young males to measure thigh muscle areas but did not measure fat content (Narici et al., 1988). In the present study, multiple scans of the arm and leg were taken in young and aged subjects, similar to the approach by Maughan, et al. (1984) for the forearm of younger adults, in order to determine the anatomical CSA. Multiple scans allow for a more detailed examination of total limb composition and, together with geometrical assumptions of limb shape, provide a means for estimating limb component volumes *in vivo*. In addition, the muscle physiological cross-sectional area (PCSA), an *in vivo* measure not previously available, can be estimated from muscle volumes calculated using these methods (Edgerton et al., 1986).

3.2 METHODS

3.2.1 Subjects and Anthropometry

Informed consent was obtained from 7 young (25 - 38y) and 13 elderly (65 - 90y) males. All subjects were ambulatory, and not sedentary, nor highly trained. None had any known neuromuscular or circulatory pathologies. Anthropometric measures of height, weight, and right arm and leg lengths were taken. Arm length was measured using a flexible metal tape, with the arm supported at the wrist, abducted to 90°, elbow extended and forearm semipronated. Total arm length was defined as the distance from the most proximal point of the arm at which a girth measure could be taken (limited by the posterior axillary fold) to the narrowest girth just proximal to the lateral epicondyle of the humerus. Leg length was measured using an anthropometer with the subject freely standing and was taken as the distance from the head of the fibula to the narrowest girth of the leg, usually slightly proximal to the lateral malleolus. Triceps and biceps skinfolds were measured using Harpenden calipers with the upper limb in the dependant position. Medial and lateral calf skinfolds were taken with the subject seated. All anthropometric measurements followed the procedures outlined by Lohman, et al. (1988). Girth, lengths and skinfold values were recorded to the nearest millimeter.

3.2.2 Computed Tomography

A series of 10 scans, 5 of the right arm and 5 of the right leg were taken on each subject. Marks were made on the skin to indicate the 5 levels for each CT slice. For the arm, the mid-distance between the two extreme points, previously described, was estimated and then a mid-distance in each half segment was identified. This method divided the arm into four nearly equidistant segments. For the leg, a third point was established at the level of greatest girth, which did not usually correspond to the mid-point between the two extremes. A mid-distance point was then found in each of the two segments. This method usually resulted in the creation of two upper equidistant segments and two lower equidistant, but longer, segments. In any case, the actual distances between each of the limb marks were measured with a steel tape, or an anthropometer for the arm and leg, respectively.

For arm scans, the subject was seated with his arm abducted to 90^{o} and supported on the other side of the CT gantry by a sling attached to his wrist. Leg scans were taken with the subject supine on the scanner table with the left (non-scanned) lower limb flexed at the hip and knee, while the right lower limb was extended and supported at the heel so that the leg was free from compression. Using a light beam in the scanner gantry to align the scan with the marks on the limbs, the scanner (Siemens, Somatom DRH) made an 8mm transverse cross-sectional scan at each of the five levels. The time for each slice was approximately two seconds using a 360^{o} scan angle and exposure settings of 125 kV and 20 mA. These exposure parameters allowed adequate visualization of limb tissues, while maintaining a low radiation dose.

With these procedures, the total fraction of the body being exposed is about 5% by mass considering both the volume of the slice and the radiation scatter. The radiation is directed only to very isolated portions of the limbs and, according to the International Commission on Radiological Protection (RCRP), only bone carries a significant weighting factor to consider for an absorbed dose of radiation in the limbs. Therefore, the total effective dose equivalent with the above settings would amount to approximately 0.02mSv, well below the yearly allowable maximum. These procedures were approved by the University Standing Committee on Human Research.

3.2.3 Data Analyses

The images (512 x 512 pixel matrix) were stored and later analyzed using a BSP 11 image computer linked with a PDP 11/24 computer. Using a pen cursor, the perimeters of various regions of interest (ROI) in each scan were outlined and an area measure calculated for each one. These regions included, total limb, total muscle plus bone, bone, and in the arm, elbow extensor and flexor muscle groups, and in the leg, the plantar flexor group. A measure for skin plus subcutaneous tissue area (SST) was calculated by subtraction. Based on a reduced density compared with muscle, portions of non-muscle tissue (fat, areolar connective tissue) within an outlined muscle region were computer highlighted and an associated area value provided. The density range chosen to highlight these non-muscle regions (NMT) was -100 to +25 Hounsfield units (HU). Average "pure" muscle density usually ranges from approximately +40 to +80 HU, depending on the CT system (Bulcke et al., 1979; Jones et al., 1983). New areas represe-nting the actual amount of muscle tissue within a region were calculated by subtraction of the highlighted areas from the total muscle compartment area.

Although the scanner was calibrated regularly with air and with water phantoms to ensure the consistency and accuracy of density determinations (mean error $\pm$ 3 HU), a plexiglass and water phantom of known diameter was also scanned to determine the error of area measurement. This error was <0.6%. To determine the reproducibility of measurement, 30 limb component regions from a number of scans were measured twice by one individual who ultimately performed all measurements. The average intra-observer difference was 2.2%. Since there is a certain amount of subjective interpretation in choosing the boundary of specific muscle groups from the whole limb cross-section, two different observers separately measured 14 different muscle regions from several scans. The average inter-observer difference in area measurements was 2.7%.

Volumes, corresponding to the various cross-sectional measured components, were estimated for each limb by assuming that each of the four segments represented the shape of a truncated cone (Jones and Pearson, 1969; Maughan et al., 1984). The formula is: $V = 1/3h(a + \sqrt{ab} + b)$, where V = segment volume (cm^3), h = length of the segment (cm), and a and b = CSA (cm^2) of the particular component for each end of the segment. Total limb component volumes were calculated by summation of the four constitutive segments. Muscle regions with non-muscle tissue eliminated, and skin plus subcutaneous tissue volumes were calculated by subtraction.

3.2.4 Statistical Analyses

Independent Student's t-tests were used to compare area and volume differences between young and old groups. Stepwise multiple linear regressions were performed to predict a component volume from single scan CSA measures and limb length.

3.3 RESULTS

There were no significant differences in the weight, overall height and leg length of the two groups, but the older group had significantly longer arm length (Table 4) Typical CT images of limbs from young and aged subjects, with indicated muscle groups outlined, are shown in figures 4 and 5.

The results of the CSA measurements for both groups are presented in Tables 5 and 6 for arms and legs, respectively. Leg areas were measured from the CT scan at greatest limb girth (middle scan) which corresponded to the largest plantar flexor area. All arm CSA results, except for the elbow flexor measures, were taken from the middle scan (number 3) which corresponded to the largest elbow extensor area. The elbow flexor measurements were calculated from the adjacent distal scan (number 4) since this level corresponded to the largest flexor area.

TABLE 4. Subject Characteristics

	Young (n=7)	Old (n=13)
Age (y)	31.4 ± 4.3 (25-38)	74.8 ± 7.1 (65-90)
Weight (kg)	74.1 ± 5.1 (68.0-84.0)	77.8 ± 9.7 (63.9-94.0)
Height (cm)	176.5 ± 5.0 (170.0-183.0)	179.4 ± 5.5 (172.0-190.5)
Arm length (cm)	19.9 ± 1.5 (18.8-22.2)	23.6 ± 1.9* (21.3-27.0)
Leg length (cm)	27.1 ± 2.4 (23.7-30.4)	29.3 ± 2.5 (26.0-34.1)
Mid-arm girth (cm)	30.4 ± 1.7 (28.0-33.1)	28.9 ± 1.9 (25.5-31.6)
Mid-leg girth (cm)	37.5 ± 1.4 (35.1-38.5)	35.9 ± 2.5 (32.8-37.5)
Biceps skinfold (mm)	4.5 ± 2.5 (2.0-6.0)	5.8 ± 2.7 (3.5-8.3)
Triceps skinfold (mm)	7.4 ± 2.6 (5.0-10.2)	11.5 ± 3.6* (6.3-16.0)
Medial calf skinfold (mm)	7.1 ± 2.6 (4.8-9.9)	10.4 ± 2.8* (7.0-13.8)
Lateral calf skinfold (mm)	7.3 ± 2.8 (5.0-9.5)	9.9 ± 4.4 (6.0-14.8)
Humerus area (cm^2)[1]	5.2 ± 0.43	5.3 ± 0.06
Tibia plus fibula area (cm^2)[1]	9.3 ± 1.2	9.4 ± 1.2

Values are mean ± SD and range in brackets.

* $p<0.05$

1 - determined from computed tomography scan

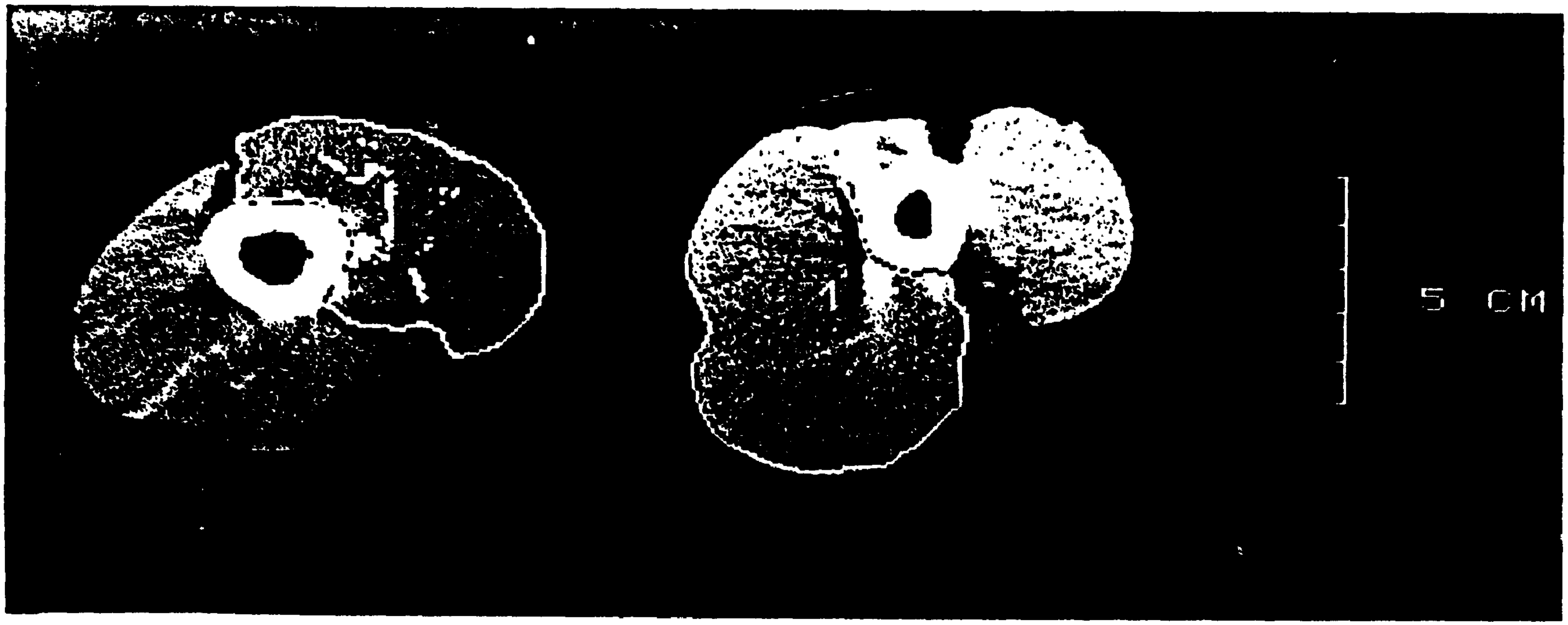

Fig. 4 Computed tomography cross-section of right arms from an 83y old (left), and a 27y old (right). Elbow flexor group is outlined in the arm on the left (old) and the non-muscle tissue regions highlighted. The level of the scan (number 4) in the old arm corresponds to the largest elbow flexor CSA and is one scan distal (approximately 5 cm) to the young arm on the right. In the young arm (right) the elbow extensor region is outlined.

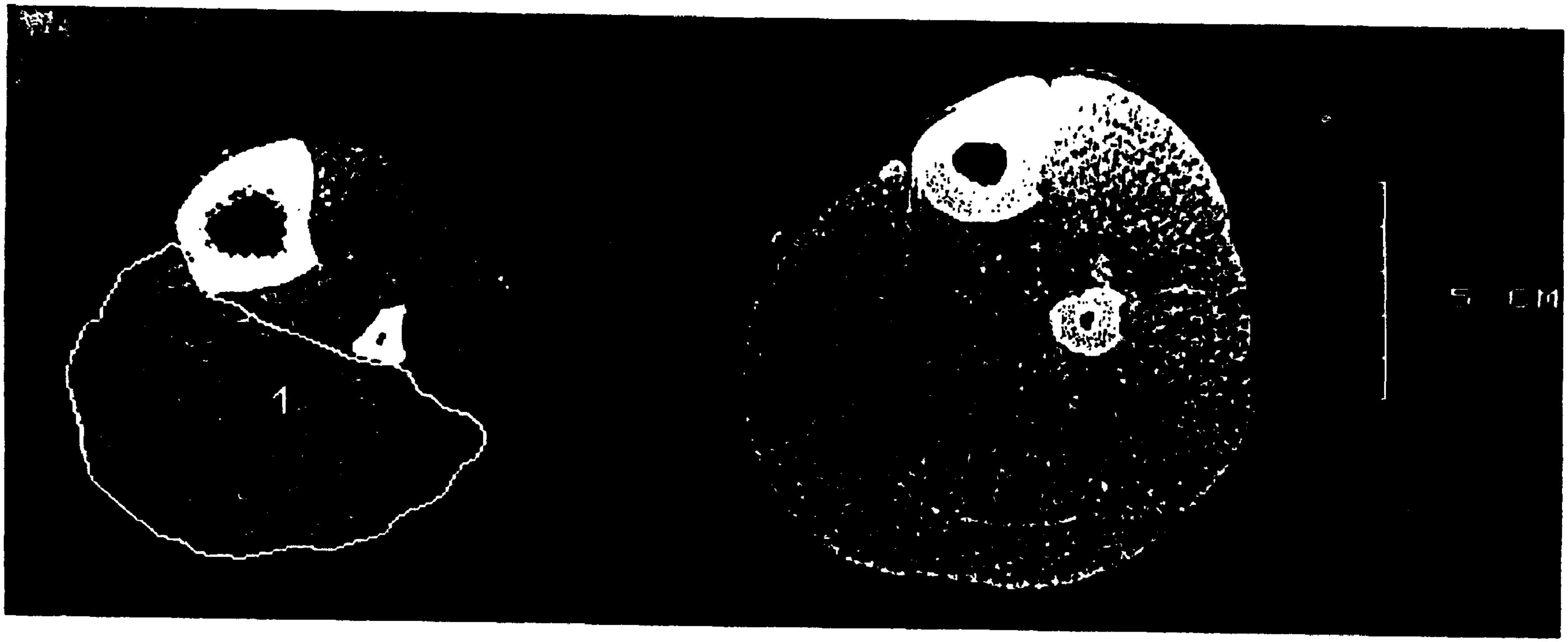

Fig. 5 Computed tomography cross-section of left legs at the level of maximum girth from an 83y old (left) and a 27y old (right). The region outlined in the old leg (left) is the plantar flexor compartment. Less dense areas, not highlighted but appearing as black regions, correspond to non-muscle tissue within the outlined region.

Table 5. Cross-sectional Areas of Arm Components Measured From CT Scan

Limb Component (cm^2)	Young (n=7)	Old (n=13)	P-value
Total Arm	74.2 ± 9.3 (61.6 - 85.6)	68.5 ± 9.6 (52.4 - 83.5)	0.218
Total muscle plus bone	59.7 ± 6.9 (49.5 - 69.8)	45.4 ± 4.9 (38.3 - 55.6)	<0.001
Skin plus subcutaneous fat	14.5 ± 7.5 (6.1 - 24.9)	23.1 ± 6.9 (12.5 - 35.1)	0.021
Elbow extensor compartment	31.9 ± 5.2 (24.8 - 40.9)	23.9 ± 2.4 (20.3 - 28.2)	0.005
Non-muscle tissue within extensor compartment	1.5 ± 0.47 (0.9 - 2.0)	2.06 ± 1.3 (0.75 - 5.9)	0.200
Elbow extensor muscle	30.4 ± 5.2 (23.9 - 39.8)	21.8 ± 2.4 (18.6 - 26.1)	0.004
Elbow flexor compartment	26.5 ± 5.1 (20.7 - 33.7)	18.3 ± 3.5 (12.3 - 23.1)	0.001
Non-muscle tissue within flexor compartment	1.1 ± 0.41 (0.6 - 1.8)	2.0 ± 1.1 (0.9 - 5.4)	0.020
Elbow flexor muscle	25.4 ± 5.5 (18.8 - 33.0)	16.3 ± 3.9 (9.9 - 21.7)	<0.001
Bone	5.2 ± 0.43 (4.7 - 5.8)	5.3 ± 0.6 (4.1 - 6.2)	0.835

Values are means ± SD and range in brackets.

P-value refers to significance of t-statistic determined from independent students' t-test.

All measurements made from CT scan at largest arm girth, except elbow flexor values which were taken from the next distal scan.

Table 6. Cross-sectional Areas of Leg Components Measured From CT Scan Taken at Largest Leg Girth

Limb Component (cm^2)	Young (n=7)	Old (n=13)	P-value
Total Leg	109.8 ± 8.5 (98.6 - 122.0)	98.8 ± 13.2 (71.3 - 119.0)	0.063
Total muscle plus bone	97.6 ± 8.6 (82.7 - 111.0)	84.8 ± 10.3 (65.5 - 103.0)	0.012
Skin plus subcutaneous fat	12.3 ± 4.8 (5.7 - 19.0)	14.0 ± 5.1 (5.8 - 25.6)	0.456
Plantar flexor compartment	60.3 ± 6.2 (51.6 - 71.7)	46.8 ± 5.3 (36.8 - 56.1)	<0.001
Non-muscle tissue within plantar flexor compartment	1.6 ± 0.70 (0.78 - 2.7)	8.6 ± 7.1 (1.5 - 26.0)	0.004
Plantar flexor muscle	58.4 ± 6.5 (50.4 - 70.6)	38.2 ± 8.4 (21.2 - 48.1)	<0.001
Bone	9.3 ± 1.2 (7.0 - 10.5)	9.4 ± 1.2 (7.5 - 11.2)	0.806

Values are mean ± SD and range in brackets.

P-value refers to the probability of the t statistic determined from independent Student's t-test.

The arms from the aged individuals had significantly smaller muscle plus bone CSA, but there was no difference between the groups in total arm CSA. This resulted in a greater skin plus subcutaneous tissue area in the aged subjects. Total elbow flexor and extensor regions and total elbow extensor and flexor muscle areas were significantly larger in the young men compared with the aged men (Table 5). Only the elbow flexor region of the elderly group showed a significantly greater amount of non-muscle tissue. Arm bone areas were similar for each group. The estimated volumes for the various arm components are given for each group in Table 7. Except for the addition of a significantly greater amount of non-muscle tissue within the elbow extensor region of the aged men, and a greater bone volume, the between group results for the corresponding volume components are the same as the area values in Table 5. The larger non-muscle tissue and arm bone volumes of the aged subjects are due to a significantly longer limb (Table 4). There was no difference between the groups for total leg, or skin plus subcutaneous tissue CSA, but the total muscle plus bone CSA was significantly smaller in the old group (Table 6). The older group also had a significantly smaller plantar flexor region CSA and a greater amount of non-muscle tissue within this region. This resulted in a significantly smaller plantar flexor muscle area in the older men compared with the young men (Table 6). There was

Table 7. Estimated Component Arm Volumes

Limb Component (cm^3)	Young (n=7)	Old (n=13)	P-value
Total Arm	1546.6 ± 65.1 (1445.1 - 1641.1)	1741.2 ± 297.4 (1252.6 - 2352.9)	0.040
Total muscle plus bone	1249.4 ± 125.7 (1013.1 - 1386.1)	1173.8 ± 174.3 (923.7 - 1498.8)	0.326
Skin plus subcutaneous fat	296.8 ± 140.1 (151.4 - 504.1)	565.9 ± 171.3 (299.6 - 853.7)	0.002
Elbow extensor compartment	531.1 ± 67.5 (427.4 - 646.6)	407.6 ± 52.3 (337.8 - 522.8)	<0.001
Non-muscle tissue within extensor compartment	27.0 ± 8.7 (8.7 - 41.7)	41.4 ± 21.4 (18.2 - 103.0)	0.049
Elbow extensor muscle	504.1 ± 71.7 (397.7 - 628.7)	366.2 ± 51.3 (293.9 - 470.9)	<0.001
Elbow flexor compartment	392.9 ± 73.5 (292.4 - 530.3)	297.7 ± 38.7 (230.9 - 339.4)	0.001
Non-muscle tissue within flexor compartment	21.8 ± 7.8 (13.1 - 37.8)	38.3 ± 20.3 (16.1 - 96.4)	0.018
Elbow flexor muscle	371.2 ± 75.9 (273.7 - 512.1)	259.4 ± 48.0 (148.5 - 301.9)	0.001
Bone	108.5 ± 13.7 (92.4 - 131.9)	133.2 ± 22.3 (90.4 - 170.7)	0.016

Values are mean ± SD and range in brackets.

P-value refers to the probability of t statistic determined from independent Students' t-test.

Volumes are sums of 4 segmental volumes calculated from area and distance measures of 5 CT scans.

no difference in leg bone CSA between the groups. The estimated component leg volume measurements (Table 8) followed the same pattern for group differences as the corresponding area measurements in Table 6, except the difference between muscle plus bone volumes was not significant.

Since the equation for estimating volume contains both area and length measures, they, along with group (young, old), were entered into the multiple regression analyses as independent variables to predict related component volumes. The results of these analyses are presented as predictive equations in Tables 9 and 10 for arm and leg, respectively. All predictive variables included in the equations were independently and significantly related to the indicated dependent variable. Various combinations of the independent variables for the equations, explained from 68.9% to 94.1% of the total variance (R^2) of a particular regression. For predictions of all volumes except bone, the related CSA variable entered first into the equation accounted for 50% to 92% of the variance. The second variable, limb length, added between 3% and 33% to the total explained variance. The equations for which group was a significant explanatory variable only added between 2% and 5% to the total explained variance. Length was the foremost explanatory variable for predicting bone volumes and accounted for 61% to 76% of the variance followed by bone CSA which added from 16% to 25% to the total.

Table 8. Estimated Component Leg Volumes

Limb Component (cm^3)	Young (n=7)	Old (n=13)	P-value
Total leg	2244.4 ± 190.8 (1983.3 - 2491.5)	2297.4 ± 352.9 (1636.5 - 2990.8)	0.718
Total muscle plus bone	1911.7 ± 183.2 (1738.3 - 2266.1)	1905.0 ± 279.2 (1440.9 - 2479.1)	0.955
Skin plus subcutaneous fat	330.9 ± 120.5 (177.9 - 481.5)	390.5 ± 121.6 (194.2 - 658.9)	0.308
Plantar flexor compartment	1082.2 ± 81.9 (1004.1 - 1238.2)	933.9 ± 129.3 (701.6 - 1198.9)	0.014
Non-muscle tissue within plantor flexor compartment	36.9 ± 11.6 (11.6 - 58.1)	180.5 ± 143.1 (31.5 - 544.5)	0.004
Plantar flexor muscle	1045.3 ± 85.2 (977.6 - 1206.8)	753.4 ± 140.8 (499.4 - 1006.3)	<0.001
Bone	303.2 ± 42.5 (246.5 - 370.9)	353.9 ± 64.5 (219.7 - 437.3)	0.079

Values are means ± SD and range in brackets

P-value refers to the probability of the t statistic determined from independent Student's t-test.

Volumes are sums of 4 segmental volumes calculated from area and distance measures of 5 CT scans

Table 9. Regression Equations Relating Component Arm Areas from a single CT Scan and Lengths to Volumes

Dependent Variable (cm^3)	Independent Variables	R^2 (%)
Arm volume	= CSA arm(20.3) + arm length(81.3)-1572.2 SEE = 69.5 cm^3 (4.2%)	94.1
Muscle plus bone volume	= CSA muscle and bone (19.3)+ arm length(57.7)-1062.4 SEE = 57.0 cm^3 (4.7%)	88.4
Elbow extensor compartment volume	= CSA extensor compartment (13.1) + 100.95 SEE = 46.7 cm^3 (9.9%)	68.9
Elbow extensor muscle volume	= CSA extensor muscle (13.9) + 66.8 SEE = 45.7 cm^3 (10.5%)	73.9
Elbow flexor compartment volume	= CSA flexor compartment (12.0)+ arm length(11.8) -201.1 (if 65-90y), or -161.0 (if 25-38y) SEE = 24.8 cm^3 (7.1%)	89.3
Elbow flexor muscle volume	= CSA flexor muscle (12.5)+ arm length(11.8) -223.7 (if 65-90y), or -182.4 (if 25-38y) SEE = 24.6 cm^3 (7.8%)	91.8
Bone volume	= Arm length (6.8) + CSA bone (19.3) - 128.3 SEE = 6.8 cm^3 (5.6%)	92.2

CSA is in cm^2 and arm length in cm. SEE = standard error of estimate. R^2 is percentage of total explained variance.

All independent variables were significantly ($p \leq 0.01$) related to the dependent variable.

Table 10. Regression Equations Relating Component Leg Areas from a Single CT Scan and Lengths to Volumes

Dependent Variable (cm^3)	Independent Variables	R^2 (%)
Leg volume	= leg CSA(20.1) + leg length(55.1) -1305.3 (if 65-90y), or -1460.3 (if 25-38y) SEE = 97.8cm^3 (4.3%)	91.1
Muscle plus bone volume	= CSA muscle and bone(18.9)+ leg length(48.2) -1107.0 (if 65-90y), or -1238.7 (if 25-38y) SEE = 82.4cm^3 (4.3%)	90.4
Plantar flexor compartment volume	= CSA plantar flexor compartment(14.4) + leg length(17.4) -251.7 SEE = 53.8cm^3 (5.3%)	94.6
Plantar flexor muscle volume	= CSA plantar flexor muscle(15.1) + leg length(11.9) -168.8 SEE = 44.5cm^3 (4.9%)	94.1
Bone volume	= leg length(15.9) + CSA bone(27.3) - 375.0 SEE = 23.3 (7.1%)	86.5

CSA is in cm^2 and arm length in cm. SEE = standard error of estimate. R^2 is percentage of total explained variance.

All independent variables were significantly ($p \leq 0.01$) related to the dependent variable.

3.4 DISCUSSION

Although other studies have used CT scans to examine limb morphology and measure some component areas, primarily in younger adults (<50y), this is the first study that has taken multiple CT scans of arms and legs in the same individuals from two widely separated age groups. Total limb volumes and total muscle and bone volumes have customarily been determined by water displacement and anthropometric measures (Jones and Pearson, 1969; Maughan et al., 1984; deKoning et al., 1986), but only from cadaver specimens has it been possible to measure individual muscle group volumes (Edgerton et al., 1986).

This study has shown that, although total limb size is similar in both age groups, aged subjects have significantly smaller muscle areas and volumes and a larger component of skin plus subcutaneous tissue. In addition, infiltration of a particular muscle group by fat and other non-muscle tissues was greater in the old group, and was particulary pronounced in the plantar flexors of the 'older' elderly men. This tissue has been quantified and subtracted from the muscle region to yield an area or volume measure of lean muscle tissue.

The muscle compartments of the young subjects in this study contained from 3% to 5% NMT. A similar range was reported by Jones, et al. (1983) for young adult calf muscles.

Total CSA of the arm flexors and extensors of the aged subjects were 31% and 25% smaller, respectively, than for the young subjects, whereas the plantar flexor compartment CSA of the older men was only 22% smaller. When non-muscle tissue within these regions was considered in comparison to the young, the arm flexors and extensors of the older men contained 27% and 45% more non-muscle tissue, respectively, but the plantar flexors contained 81% more than in the young. The net effect is that all three muscle groups showed a similar reduction in "pure" muscle area in the elderly of 28%, 36% and 35% for the elbow extensors, flexors and plantar flexors, respectively (Tables 5 to 8). As stated above, the largest infiltration of NMT was noted in the plantar flexors of the 'older' elderly. This may suggest an accelerated infiltration of NMT in the plantar flexors after age 70 to 75 years. In contrast, the skin plus subcutaneous CSA or volume was not different in the legs of the two groups, but the aged subjects showed a significantly larger amount in their arms.

Apart from a few single scan imaging studies, most investigators have examined muscle areas and masses for these particular muscle groups from cadavers and amputated limbs (Alexander and Vernon, 1975; Amis et al., 1979; Wickiewicz et al., 1983; Edgerton et al., 1986; Brand et al., 1986). Only one imaging study, limited to the triceps surae, has reported CSA measurements for an elderly (82y to 100y) population

(Vandervoort and McComas, 1986). The larger values obtained in this study for both age groups are most likely a result of the inclusion of most muscles of the posterior compartment. Other ultrasound (Ikegawa et al., 1987) and CT studies (Bulcke et al., 1979; Termote et al., 1980; Jones et al., 1983) in younger males (17 - 50 years) have, however, reported plantar flexor areas very close to the mean value in this study.

Single scan arm imaging studies in younger subjects (20 to 50 years) have shown comparable values to this study for CT measured total arm area (Schmidtbleicher and Buehrle, 1987), arm muscle plus bone area (deKoning et al., 1986), elbow extensors (Shantz et al., 1983; Schmidtbleicher and Buehrle, 1987) and elbow flexors measured with ultrasound (Ikai and Fukunaga, 1968). Some CT studies have measured only the biceps brachii group of the elbow flexors (Nygaard et al., 1983; MacDougall et al., 1984) which makes comparisons difficult since in this study, all flexors of the anterior compartment were included. Ikegawa, et al. (1987) using ultrasound, reported smaller arm flexor and extensor values than in this study, but their subjects were of a substantially smaller stature and weight. No arm imaging measures have been reported for elderly subjects (>65 years).

Two imaging studies have used multiple limb scans; one of the thigh (Narici et al., 1988) and one of the forearm (Maughan et al., 1984). Both these studies were limited to younger individuals (<35y) and only Maughan, et al. (1984) calculated various limb component volumes. Neither study measured the amount of non-muscle tissue located within a muscle compartment. Validation and comparison of the results in this study are therefore limited to results from *in vitro* post-mortem studies.

There are some inherent problems with these *in vitro* results which should be considered before any comparisons are made. First, the number of subjects from these investigations are usually limited to less than 6 and often only one cadaver was used (see Appendix I). Secondly, and more importantly, there is a lack of information concerning pre-death history and unless the individuals were sudden death victims, it is reasonable to assume that they were aged and were likely inactive or debilitated for a prolonged period of time before death. Amputations, on which some studies are based, are often performed due to disease and it is well known that both disease and inactivity can have profound negative effects on muscle size (Edgerton et al., 1986). Bearing in mind these *in vitro* limitations, comparisons of the *in vivo* muscle volumes can be made, but first, since cadaver studies usually report a weight of a muscle, appropriate conversions are necessary using the following formula: $V = m \times p$, where V = volume (cm^3), m = mass (g), and p = density, taken as 1.056 g/cm^2 from Mendez and Keys (1960).

Elbow flexor and extensor masses from cadaver studies by Amis, et al. (1979), An, et al. (1981), and Edgerton, et al. (1986) are within the range of the aged men in this study (Table 7), as are plantar flexor volumes given by Alexander and Vernon (1975), Wickiewicz, et al. (1983), and Brand, et al. (1986) (Table 8). Elbow flexor, extensor, and plantar flexor volumes approximated from those studies are 213 cm^3, 300 cm^3, and 740 cm^3, respectively, compared with "pure" muscle tissue values of 260 cm^3, 366 cm^3, and 753 cm^3 in this study.

The limitations of this CT method for volume determination are that it is not possible to distinguish muscle from tendon, and it is sometimes difficult to delimit a particular muscle from other muscles not actually part of the group, particularly near joints. By comparison with the <u>in vitro</u> results above, it does not appear, however, that these limitations have affected substantially <u>in vivo</u> determinations. The benefit of knowing muscle volume is that it allows for calculation of the physiological cross-sectional area (PCSA), which is a more meaningful measure when normalizing force for amount of muscle tissue (specific tension) (Edgerton et al., 1986; Maughan et al., 1986) (see Appendix I for further details).

To calculate <u>in vivo</u> volumes and to account for muscle group size variations within a limb segment, multiple imaging scans are required. But due to various restrictions, including ionizing radiation, these are not always feasible to apply to large numbers of subjects. The regression equations given in Tables 9 and 10, however, permit very reasonable predictions of limb volume components from corresponding component areas (measured from a single scan at the largest muscle girth) and total segment length. The area and length measures were sufficient in the prediction of volume, such that in only a few cases, and with limited impact, did group (young, old) have a significant effect.

The results of this study have important implications for the determination of limb composition from anthropometric measures, especially for aged subjects. Knowledge of muscle tissue amounts is of considerable importance when strength measures are compared between these groups. The predictive equations also offer a method to derive muscle volumes which, then permit an in vivo estimate of PCSA (Wickiewicz et al., 1983; Edgerton et al., 1986) (see Appendix I).

CHAPTER FOUR

ANTHROPOMETRIC DETERMINATION OF ARM AND LEG COMPOSITION IN YOUNG AND AGED MEN

4.1 INTRODUCTION

Simple anthropometic measures of limb girth and skinfold thicknesses are often used to estimate total limb volume and total muscle plus bone areas or volumes (Jones and Pearson, 1969; Heymsfield et al., 1982; deKoning et al., 1986). Jones and Pearson (1969) used water displacement and conventional soft-tissue X-ray to validate their lower limb anthropometric estimates in young adults, whereas Heymsfield, et al. (1982) and deKoning, et al. (1986) used single scan transverse computed tomography (CT) to validate arm anthropometric methods in individuals aged 20 to 70 years. These anthropometric methods have been implemented in many investigations, but frequently applied to populations for which they have not been validated. This is especially evident for the lower limb method of Jones and Pearson (1969) which has often been used to normalize strength capacities in children (Davies et al., 1983), atrophied legs (White and Davies, 1984) and older individuals (Makrides et al., 1985; Pearson et al., 1985). Subsequent corroboration of the methods of Jones and Pearson (1969) using more up-to-date imaging techniques has also not been undertaken for any population. Arm anthropometric methods have often been applied to individuals older than the subjects used in the validation studies (>70y) (Burr and Phillips, 1984; Pearson et al., 1985; Chumlea et al., 1986).

The relative simplicity of these methods to provide an estimate of fat-corrected total limb muscle plus bone size compared with more sophisticated imaging procedures, probably accounts for their widespread useage. However, these methods are not selective and when used to normalize muscle strength, they do not measure the size of the particular muscle group associated with the movement (Young et al., 1984). This selectivity is currently only available using ultrasound, computed tomography, or nuclear magnetic imaging, and for various reasons these techniques are impractical to apply to large numbers of subjects. The purpose of this study was to compare the anthropometric determination of leg and arm composition in young and aged males, with results obtained by computed tomography.

4.2 METHODS

4.2.1 Subjects

Subjects and description are the same as the previous chapter, see page 32.

4.2.2 Anthropometry

Details are the same as the previous chapter (see pages 32 - 33), except for the following additional explanation pertinent to this chapter.

Total limb cross-sectional area (CSA) and muscle plus bone CSA (MBCSA) were determined at each of the five girth levels. The cross-sectional shape of each limb was assumed to represent a circle and appropriate equations were used for calculating this area, and the fat-corrected muscle plus bone area (deKoning et al., 1986). Total limb volumes and muscle plus bone volumes were estimated by summation of the volumes of the four constitutive segments, calculated by assuming each represented the shape of a truncated cone (Jones and Pearson, 1969). CSA or volume of skin plus subcutaneous tissue (SST) were calculated by subtraction.

4.2.3 Computed Tomography

Details have been described in the previous chapter, see pages 33 - 34.

4.2.4 Statistical Procedures

Pearson correlations and paired t-tests were used to compare anthropometric (AP) and CT measurements in each group. Since the number of subjects in the young group was small (7), non-parametric tests (Spearman correlation and Wilcoxon rank) were also performed, but the results were not appreciably different from the parametric tests. Independent t-tests compared differences between the two groups for AP and CT measures.

Multiple linear regression analyses were used to predict CT determined areas and volumes from anthropometric measures. Each group was treated separately since it has been shown that age has a significant effect on body composition equations for which the linear model is not appropriate (Pollock and Jackson, 1984). Since the number of subjects in each group was small, only one independent variable was entered in any regression run for the young group, and a maximum of two for the old group (Jackson, 1984).

4.3 RESULTS

The physical characteristics of the subjects are given in Table 4 (previous chapter, page 38). Arm length was significantly ($p \leq 0.05$) greater in the old group, and the triceps and medial calf skinfolds were significantly smaller in the young group. There were no differences between CT determined bone areas.

There was no difference in total arm CSA between the groups from either CT or AP determinations, but, because the older men had longer arms their total arm volumes were significantly larger than the young men. The AP arm skin plus subcutaneous (SST) CSA and volume were not different between the groups, but the CT values were significantly larger in the aged group. For both AP and CT measures, the aged group had a significantly smaller arm muscle plus bone area (MBCSA) than the young. The between group difference in muscle plus bone volume (MBV), however, was not significant because of the longer arms in the group of older men. In the leg, both AP and computed tomography MCSA's were significantly smaller in the aged men; all other measures were not different between groups.

Individual muscle group values determined from CT for both CSA and volume were significantly smaller in the aged individuals (Tables 11 and 12). The plantar flexors represented approximately 53% of the total leg area or volume in the young, and approximately 44% in the aged men. Non-muscle tissue (NMT) occupied approximately 3% and 18% of the plantar flexor compartment in the young and old groups, respectively. The elbow flexors and extensors for the young represented approximately 36% and 43%, respectively of the total arm CSA and 25% and 34%, respectively of the total volume. NMT accounted for approximately 5% of the arm flexor or extensor compartments. The arm flexors and extensors of the aged men occupied approximately 27% and 35%, respectively of the total arm CSA and 17% and 23%, respectively of the total volume. Arm flexor and extensor compartments of the aged men contained approximately 10% NMT.

Table 11. Comparison of Limb Component Areas Determined by CT Scan and Anthropometry in Arms and Legs of Young and Old Males

Component		YOUNG (n = 7)	correlation (r)	t-test (p value)	OLD (n = 13)	correlation (r)	t-test (p value)
Total arm area (cm^2)	CT	74.2 ± 9.3			68.5 ± 9.6		
	AP	73.8 ± 8.1	0.87	0.830	66.7 ± 8.8	0.96	0.036
Arm (MBA) (cm^2)	CT	59.7 ± 6.9			45.4 ± 4.9*		
	AP	65.0 ± 7.6	0.91	0.004	54.7 ± 5.9*	0.83	<0.001
Arm SST area (Cm^2)	CT	14.5 ± 7.5			23.0 ± 6.9*		
	AP	8.8 ± 3.1	0.97	0.016	12.1 ± 4.6	0.78	<0.001
Total leg area (cm^2)	CT	109.8 ± 8.5			98.8 ± 13.2		
	AP	111.8 ± 8.5	0.98	0.018	103.0 ± 14.1	0.87	0.049
Leg MBA (cm^2)	CT	97.6 ± 8.6			84.8 ± 10.3*		
	AP	98.8 ± 9.4	0.99	0.063	85.5 ± 11.1*	0.74	0.745
Leg SST area (cm^2)	CT	12.3 ± 4.8			14.0 ± 5.0		
	AP	12.9 ± 4.8	0.98	0.046	17.6 ± 6.3	0.87	0.002

Values are means ± SD

CT is computed tomography, AP is anthropometry, MBA is muscle plus bone area, and SST is skin plus subcutaneous tissue.

t-test p value refers to the probability of a difference between CT and AP values (paired t-test).

*refers to a significant difference ($p<0.05$) between young and old for the indicated variable (independent t-test).

Table 12. Comparison of Limb Component Volumes Determined by Multiple CT Scans and Anthropometry in Arms and Legs of Young and Old Males

Component		YOUNG (n = 7)	correlation (r)	t-test (p value)	OLD (n = 13)	correlation (r)	t-test (p value)
Total arm volume (cm^3)	CT	1546.6 ± 65.1			1741.2 ± 297.4*		
	AP	1516.8 ± 72.6	0.89	0.500	1689.1 ± 302.1*	0.97	0.033
Arm MBV (cm^3)	CT	1249.4 ± 125.7			1173.8 ± 174.2		
	AP	1341.7 ± 88.5	0.83	0.015	1392.4 ± 209.8	0.88	<0.001
Arm SST (cm^3)	CT	296.8 ± 140.1			565.9 ± 171.2*		
	AP	175.0 ± 56.1	0.98	0.895	296.6 ± 124.0	0.82	<0.001
Total leg volume (cm^3)	CT	2244.3 ± 190.8			2297.3 ± 352.9		
	AP	2246.9 ± 213.5	0.98	0.895	2357.6 ± 404.1	0.98	0.031
Leg MBV (cm^3)	CT	1911.7 ± 183.2			1905.0 ± 279.2		
	AP	1948.5 ± 222.2	0.99	0.067	1908.4 ± 298.5	0.93	0.912
Leg SST (cm^3)	CT	330.9 ± 120.5			390.5 ± 121.6		
	AP	298.5 ± 118.0	0.49	0.003	449.2 ± 176.3	0.89	0.032

Values are means ± SD

CT is computed tomography, AP is anthropometry, MB is muscle plus bone volume, and SST is skin plus subcutaneous tissue.

t-test p value refers to the probability of a difference between CT and AP values (paired t-test)

*refers to a significant difference ($p<0.05$) between young and old for the indicated variable (independent t-test).

The correlations between AP and CT measures were high (0.74 to 0.99) (Tables 11 and 12), but in most cases there were significant differences between the two. Values from the two techniques were significantly different except for the young total arm CSA and volume, young and old leg MBA and volume, and young total leg volume.

Prediction equations of limb muscle group CSA and volumes from anthropometric measurements are presented in Table 13. Predictions for several dependent variables were not possible in the aged group, but for the four equations that were obtained, the errors of estimate ranged from 5.4% to 9.6%. In the young group the errors of estimate ranged from 1.4% to 15.1%. The plantar flexor areas and volumes in both groups had the smallest errors. The errors for the young group were smaller (<5.2%) than the old (<7%). In the young group prediction equations for "pure" muscle tissue (total muscle compartment less the NMT) were more difficult to obtain than for the total muscle compartment. In the old such prediction equations could not be obtained.

4.4 DISCUSSION

The anthropometric results (Table 4 of previous chapter, page 38) are comparable to the values given in other studies (Bishop et al., 1984; Frisancho, 1984; Chumlea et al., 1985; Pearson et al., 1985). For the most part, these studies were

Table 13. Prediction of Arm and Leg Muscle Areas and Volumes from Anthropometric Variables

	YOUNG (n = 7)			OLD (n = 13)		
Dependent Variable	Equation	SEE (%)	R^2%	Equation	SEE (%)	R^2%
Total flexor area[1] (cm^2)	= MBA(0.61)-13.2	2.5cm^2(9.4)	80.3			
Flexor muscle area[2] (cm^2)	= MBA(0.64)-16.4	2.7cm^2(10.6)	79.1			
Total extensor area[1] (cm^2)				= CSA(0.15)+12.1	2.1cm^2(9.6)	30.0
Total plantar flexor area[1] (cm^2)	= MBA(0.61)+0.54	2.7cm^2(4.5)	84.0	= CSA(0.31)+15.2	3.2cm^2(6.8)	66.1
Plantar flexor muscle area[2] (cm^2)	= MBA(0.62)-2.8	3.0cm^2(5.2)	82.0			
Total flexor volume[1] (cm^3)	= MBV(0.56)-361.7	59.2cm^3(15.1)	46.0			
Total extensor volume[1] (cm^3)	= MBV(0.54)-191.7	52.3cm^3(9.8)	50.0	=AVOL(0.15)+158.4	28.6cm^3(7.0)	72.5
Total plantar flexor volume[1] (cm^3)	= MBV(0.36)+374.8	15.2cm^3(1.4)	97.1	=LVOL(0.30)+233.1	50.0cm^3(5.4)	86.3
Plantar flexor muscle volume[2] (cm^3)	= MBV(0.37)+328.5	26.5cm^3(2.5)	92.0			

CSA is a total limb cross-section area and MBA is muscle plus bone area both taken from largest girth (cm^2). AVOL is total arm volume, LVOL is total leg volume and MBV is muscle plus bone volume calculated from anthropometric measures (cm^3)

1 = total area or volume of all tissue in indicated region

2 = area or volume of muscle in indicated region, excluding non-muscle tissue.

Note: blanks in the table indicate that a reasonable equation could not be obtained for prediction.

large surveys consisting of from nearly one hundred males up to 8000. The twenty subjects in this study have anthropometric values that are representative of the average population for their ages.

4.4.1 Arm Composition

Although there was a tendency for AP determined total arm area to be smaller than the CT area, it was not significant, and was probably a result of compression of the arm when using the metal tape (Heymsfield et al., 1982; deKoning et al., 1986). Arm skin plus subcutaneous tissue (SST), however, was substantially underestimated compared to CT values (39% and 47% smaller in young and old, respectively). This difference resulted in an overestimation of muscle plus bone cross sectional area (MBCSA) from anthropometry (Table 11). MBCSA's were 24% smaller in the aged men than the young men and the arm contained 37% more SST. The smaller MBCSA was due to smaller muscle mass since the bone areas were not different between groups (Table 4 of previous chapter, page 38).

The study by deKoning, et al. (1986) found very similar arm area values in males aged 20 to 50 years and also noted that AP measurements underestimated SST by 37%. Heymsfield, et al. (1982) found arm MBCSA area to be also overestimated by anthropomery, but attributed most of the error to the assumption that arm circumference represented a circular shape. It has been suggested that an elliptical model may be more suitable in some cases (Heymsfield et al., 1979), but even with the reduced arm tissue tone in aged individuals, the results of this study support deKoning, et al. (1986) that the circular model for estimating arm CSA seems appropriate. The more critical problem for these AP methods is that the proportions of the tissue amounts in the arms of the young and older arms are significantly altered although the girths are the same. This makes the accurate determination of MBCSA in aged individuals difficult to obtain since its calculation depends on the subtraction of SST from total limb size. And, it is mostly due to the error of SST determination from skinfold measures, that these methods can only provide a relative value of arm MBCSA.

4.4.2 <u>Leg Composition</u>

In spite of the tendency for limb compression when using a metal tape, total leg area was overestimated using AP compared with CT in both groups. The assumption of a circular shaped limb may be less valid in the leg than in the arm and could account for the poorer estimations of leg areas. Nevertheless, this basic assumption is usually used for these measurements since it is relatively easy to calculate and is convenient for estimating limb volumes that are based on conical shaped segments (Jones and Pearson, 1969; Heymsfield et al., 1982).

Leg SST amounts were only marginally (5%, p=0.046) overestimated in the young using AP methods, but in the old they were greatly overestimated (20%, p=0.002). Because of the over-estimation of total leg area and SST's in both the young and the old groups using AP methods, the MBCSA's (calculated by subtraction) were not different from the CT values.

Skin plus subcutaneous tissue was a smaller fraction of the total limb area in the leg than in the arm in both groups. This may have improved the AP estimation of MBCSA since, especially in the young, the two measures (CT and AP) of SST were more similar in the leg than in the arm. The SST overestimation in the leg using skinfolds was probably a result of an uneven deposition of this tissue, that is, greater on the medial and lateral sides than on posterior and anterior aspects.

Leg volume measures of SST using AP methods present a perplexing reverse pattern between the two groups compared with CT values. In the young group AP underestimated the amount of SST by almost 10%, whereas in the old group it was overestimated by 13%. This result is consistent with area estimates for the old group, but not the young. The difference for volume determinations may be that in the old, the medial and lateral calf skinfolds represent a more constant, albeit larger SST thickness throughout the leg, and therefore, the circular model of the leg may be more appropriate. The question of a better geometric representation for the leg requires further investigation.

The calf SST volumes determined by AP and soft-tissue X-ray in the study by Jones and Pearson (1969) showed that, similar to this study, AP overestimated SST by 5% (although not significantly) in young adult males. Their total leg (calf) volumes and SST volumes were much larger than the values obtained in this study. This could be partially a result of not including in this study the portion of the leg between the head of the fibula and the knee joint. A table comparing lower limb volumes and segments from a number of studies is presented in a paper by Katch, et al. (1973). The results of Jones and Pearson (1969) are by far the largest reported in the table. The average calf (leg) volumes for men and women were about 30% larger than those reported in the other studies. Although heights and weights were not given it is also possible that the subjects in Jones and Pearson's (1969) study were much larger than in the other reports. No validation studies of AP methods using water displacement or modern imaging techniques for older subjects have previously been reported.

4.4.3 Muscle Group Predictions

The ability to predict the size of individual muscles from anthropometric measures depends on the limb and the age of the subject. The plantar flexor compartment of the old group is fairly well estimated, but due to the large amount of NMT, the actual amount of muscle cannot be estimated. In the young, however, the plantar flexor compartment and plantar flexor muscle amounts can be predicted from AP methods with little error (SEE=5%). This is likely due to the plantar flexors comprising a large portion of the leg and the more accurate prediction of SST amounts from skinfold measures. There seems to be no obvious relationship between simple AP measures and the amount of NMT within a muscle compartment. This is a major limitation in aged individuals for predicting actual muscle amounts from AP methods.

Predictions of individual muscle amounts in the arm are less satisfactory. The main difficulty is that at the mid-arm level neither muscle group represents more than 40% of the total, with each group contributing equally to the total limb size. This is a prediction limitation in both age groups when arm girths are used to estimate individual muscle compartment amounts (Table 13). A further problem in the arm is that the skinfold measures (especially the triceps) do not provide a good estimate of SST amounts. Prediction errors of muscle groups in the arm are twice as large as for the leg in the young group and 30% greater in the old group. The prediction of actual ("pure") muscle group size in either limb is even poorer, although this limitation is not as important for the arm as for the leg since a smaller percentage of the arm compartments in either group was composed of NMT.

Several of the prediction equations are, however, useful as they provide a reasonable estimate of the size of a particular muscle group. This may be an improvement over using total limb MBCSA, especially if the estimate is used to normalize muscle strength. The main problem with anthropometric estimates in aged individuals is that there are substantial differences in the relative proportions of limb tissues, particularly fat, which are not apparent using surface measures. Assumptions concerning the geometric representation of both arms and legs requires further investigation.

The aged population present special difficulties for anthropometric measurements (Chumlea et al., 1984) and, apart from a few investigations using single CT limb scans (see Introduction), no studies to date have systematically validated anthropometric techniques using multiple CT scans in this population. The results of this study have identified the benefits and limitations of using AP techniques for limb composition estimates in an aged male population. The validation of the prediction equations using multiple CT scans have permitted improved estimates of the area and volume for the calf muscle in young males (cf. Jones and Pearson, 1969), and established similar useful equations for legs in the aged, and arm muscles in young and aged individuals.

CHAPTER 5

VOLUNTARY AND EVOKED RESPONSES OF THE ELBOW EXTENSORS IN AN AGED POPULATION FOLLOWING A SIX MONTH STRENGTH TRAINING PROGRAM

5.1 INTRODUCTION

It is well recognized that muscle strength declines with age (Larsson, 1982; Vandervoort et al, 1986) and that these changes are not substantial until the seventh to eighth decades of life (Green, 1986; Grimby, 1987; Lexell, 1988). Reviews by Grimby and Saltin (1983) and Green (1986) have reported several factors responsible for this decline, however, a major factor of decreased strength with ageing seems to be a loss of muscle mass, which may be secondary to the loss of motoneurons. In addition to loss and atrophy of muscle tissue, ageing may result in altered ultrastructural composition and architecture of muscle, and changes in the quality and quantity of connective tissue (adipose as well as 'true' connective tissue). The research to support these contentions is, however, limited (Vandervoort et al., 1986).

It has been shown that muscle strength can be increased in aged individuals, but most of the improvement has been attributed to central neural changes, thus prompting the suggestion that, unlike younger individuals, adaptations in muscle of aged individuals per se, are not possible, or are much delayed (Moritani and deVries, 1980; Vandervoort et al., 1986; Grimby, 1987). However, in these studies strength training has been limited to less than 12 weeks, and experiments designed to separate neural and muscle factors are limited. The purpose of this study was to strength train the elbow extensor group in aged subjects for 24 weeks and to measure both voluntary and electrically evoked muscle contractile properties. Unique aspects of this study included: 1) strength training a muscle group that is not habitually used, 2) use of a subject group averaging just over 70 years of age, and 3) the inclusion of an age and activity matched control group.

5.2 METHODS

5.2.1 Subjects

Twenty-six subjects 64 years of age or older, volunteered for the study. The study was approved by the University Standing Committee on Human Research, and informed written consent was obtained from all subjects. Six subjects were excluded from participating after a medical examination and a bicycle stress test identified physical conditions or drug therapies that were contraindicated for muscle strength training or contractile property tests. The 20 remaining subjects included 18 males and 2 females. All participants were considered moderately active for their age, although none had previously participated in any form of strength training exercises. Twelve subjects, including the 2 females, elected to be in the training group, and 8 males served as a control group. Subjects were staggered into the study in groups of 2 or 3 during the first 6 month period. However, one male subject (aged 72 yrs) trained only one arm for the first 24 weeks and then began training the other arm for the next 24 weeks, thus creating results for 13 trained arms from 12 training subjects. Measurements were taken before training, at approximately 12 weeks for the experimental group, and after approximately 24 weeks in both groups.

5.2.2 Training

The elbow extensor muscle group was exercised on a custom-built pulley and cable system, using free weights for resistance. The single pulley was suspended overhead and the subject sat on a sturdy stool with a back support, holding the cable handle with a pronated forearm, elbow flexed at 45° and the upper arm in the dependant position. The other end of the cable was attached to a weight pan resting on the floor 30 cm in front of the subject's feet. The muscle group was exercised by slowly extending the elbow (raising the weights) using strict form to minimize upper arm deviation from the dependant position. Shoulder and torso movements were also discouraged to minimize the involvement of extraneous muscles. When the extended, but not locked position of the elbow was reached ($\sim 170^{\circ}$), the weight pan was then slowly lowered as the elbow returned to the flexed position. Each complete cycle, or repetition, lasted 5-7s; 2-3s to extend the elbow and 3-4s to flex the elbow. Pauses between repetitions (reps.) were minimal (1 - 2s) and the weight pan did not contact the floor until a set was completed.

The subjects were familiarized with the exercise technique on a separate occasion, before determining a one-repetition maximum (1RM). The initial training load (for the first two weeks) was approximately 60% of the 1RM for 10 to 12 reps., and this was gradually increased to 80% of the 1RM by week 5 using 8 to 10 reps. Weights were added as strength improved such that a maximum of 8 reps. and a minimum of 6 reps. were performed for each set, using strict form. The progressive overload principle was used for the remaining 19 weeks. In each training session, four sets were alternated between arms, for a total of 8 sets. No more than 30 s of rest was permitted between the sets for each arm (right arm, left arm) and 30 s to one minute of rest was allowed after the completion of two consecutive sets. Stretching, and a warm-up set of 10-12 reps., at 50% 1RM preceded the sessions. Training sessions were 3 times per week on non-consecutive days and lasted between 15 and 20 minutes. A 45 minute leg cycle ergometer ride was performed prior to the weight training session and sufficient time was given to allow the cardiorespiratory system to return to normal before the strength exercises began. A detailed training log was kept for each subject.

5.2.3 Contractile Measurements

Dynamic concentric strength was measured before and after the program in the training group using the 1RM test. Static voluntary strength and electrically stimulated contractile properties were assessed in both groups before and after the program, and additionally in the training group at approximately 12 weeks. A specially constructed steel and aluminum dynamometer was used for these measurements (Fig. 6). The device was bolted to a sturdy bench and the subject sat in a chair with either the right or left upper limb in the device. The height of the chair was adjusted so that the upper arm was in a horizontal position in front of the subject (forward flexion of the shoulder). The dynamometer consisted of a horizontally fixed upper arm carriage and a forearm carriage that could be set to any angular position of the elbow joint from 0° (elbow extended) to 135° of elbow flexion. The forearm carriage was attached to an axle to which a strain gauge was bonded. The platforms on the upper arm and forearm carriages could be adjusted so that the elbow joint axis of rotation for each subject, approximated by the humeral condyles, could be aligned with the dynamometer axis of rotation (axle and strain gauge). Velcro straps were used to

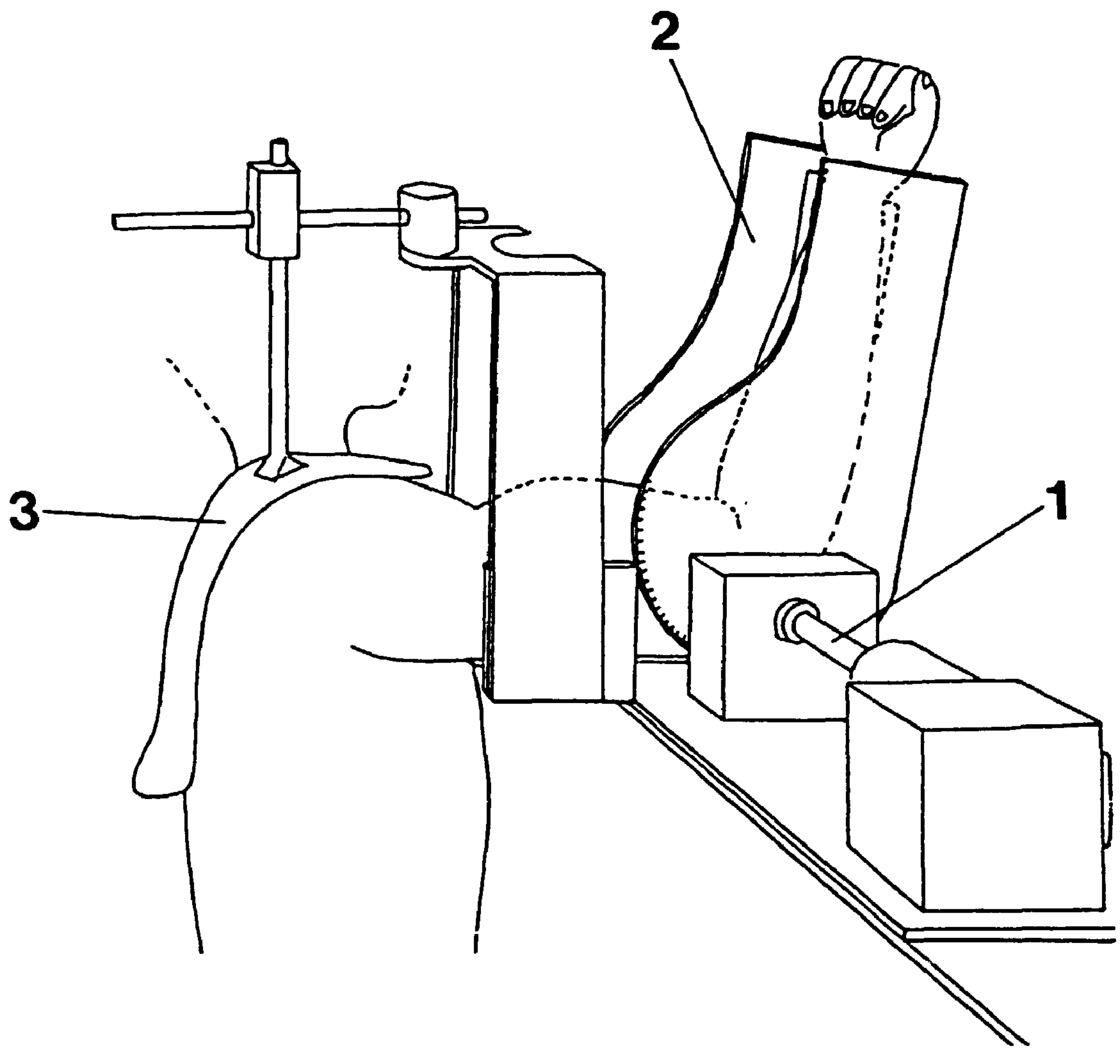

Fig. 6 Illustration of arm dynamometer used for measuring voluntary (MVC) and electrically evoked contractile properties cf elbow extensor group. Electrodes (not shown) are placed on the proximal portion of the arm over the triceps brachii. 1 = strain gauge bonded to axle, 2 = adjustable forearm carriage attached to axle, 3 = shoulder brace.

firmly attach the upper arm and the supinated forearm to the carriage platform. An inverted L-shaped shoulder brace was used to restrict posterior and upward movement of the shoulder during contraction of the elbow extensor group.

A calibration wheel was attached to the axle so that by hanging known weights from the wheel a torque calibration line and equation were calculated. The strain gauges gave a linear response (r=0.996) up to 100 N·m and the relationship remained constant ($\pm$ 2%) throughout the study. The loaded resonant frequency of the dynamometer with the limb attached was 60 Hz.

The output from the strain gauge was amplified and converted to digital form (12 bit A/D converter), viewed and stored on an IBM-PC for later analysis. In addition, twitch signals were passed through a low pass filter before A/D conversion. Analog signals for all tests were concurrently monitored on-line with an oscilloscope.

Four electrically stimulated tests and one voluntary measure of contractile function were administered during each testing session. At the beginning of the study the subjects were habituated to these tests during two visits before definitive measurements were made on a third occasion. Two surface stimulating electrodes made of brass screening covered with aluminum foil and gauze, were dampened and strapped over the elbow extensor muscle group. The larger cathode electrode (45 mm x 80 mm) was positioned postero-laterally over the proximal portions of the long and lateral heads of the triceps brachii. The anode electrode (40mm x 50mm) was positioned longtitudinally over the triceps brachii tendon approximately 6 cm proximal to the olecranon process. Muscle palpation was performed while giving electrical pulses to ensure that only the elbow extensor group was being stimulated, and small adjustments in the electrode placement were made accordingly before the subject was placed in the dynamometer. Electrical pulses were generated by a high voltage stimulator (Digitimer #3072) connected to a programmer (Digitimer #4030). An in-series custom designed volt-ammeter was used to monitor actual voltage and amperage values between the stimulating electrodes.

The order of the tests were: twitch, post-activation twitch, tetanus, maximal voluntary contraction (MVC) and fatigue. The optimum elbow angle was determined from preliminary testing (see Appendix II). For the twitch and post-activation twitch test the angle was 120° of flexion and for the remaining tests the angle was 100° of flexion.

The twitch tests consisted of three 100 μs pulses delivered at 1Hz. Voltage was increased in stepwise increments of 20 to 40 volts until supramaximal twitch tensions (Pt) were reached. The criterion for Pt was less than a 5% increase in tension between two successive voltage increments. A two minute rest was given prior to the post-activation twitch (Pt+) test in which three 100 s pulses were delivered at the Pt voltage level within 2s following a 5s MVC of the elbow extensors.

The tetanus test was administered following 2 minutes of rest. A continuous three second train of tetanic stimuli was developed from 50μs pulses and delivered to the muscle at three different frequencies (10Hz, 20Hz and 70Hz) each lasting 1 second (see Appendix II). Stimulus intensity was increased in steps of 20-40 volts following 1 minute of rest until maximal values were reached at 70Hz (Po70). The criterion for maximality was often limited by activation of antagonistic muscles which would cause a reduction in Po70 torque following a voltage increase. If supramaximal results were not possible, due to activation of the antagonistic muscles, then the greatest torque attained at 70Hz, before antagonistic influence, was used.

Two to three minutes of rest were given before and between each of the three MVC's. Strong verbal encouragement and visual on-line feedback were used to help motivate the subject. The greatest force of the three attempts was recorded.

Following a three minute rest, a two minute electrically induced fatigue test was administered. Pulses of 50μs were used to generate stimuli at 20Hz delivered for 330 ms, once per second. The intensity used was matched to the same current level recorded during the maximal tetanic test.

5.2.4 Anthropometry

Height, weight and fat corrected arm girths were taken on all subjects. Arm muscle plus bone cross-sectional areas (MBCSA) were determined by assuming the mid-arm girth represented the shape of a circle and subtracting from this girth the skin plus subcutaneous fat layer measured with Harpenden skinfold calipers (deKoning et al., 1986).

5.2.5 Statistical Analyses

The effects of the training program, before and after 24 weeks, were assessed using a multiple analysis of variance with two repeated measures to determine main effects of training. Parameters that changed significantly ($p \leq 0.05$) were then treated with an analysis of covariance. This analysis controls for any between group differences present before training and then tests for post-24 week changes. When significant ($p \leq 0.05$) changes were determined for a particular variable, within group Scheffé post-hoc tests were performed to determine the p-value for each group. The values from the 3 test sessions (0, 12 and 24 weeks) for the experimental group were separately analyzed using an analysis of variance with repeated measures. If a significant session effect was obtained from this analysis, post-hoc Scheffé tests were performed to determine the p-values between 0 and 12 weeks and 12 and 24 weeks.

5.2.6 Computer-Assisted Data Analysis

If two or three of the supramaximal twitch responses were similar in amplitude and duration they were overlayed into a single twitch, otherwise the twitch with the greatest Pt was used. Calculation of peak tension (Pt), time to peak tension (TPT), half-relaxation time (1/2 RT), peak positive dP/dt (+dP/dt), peak negative dP/dt (-dP/dt) and average positive dP/dt (dP/dta) were determined by computer from the software differentiated twitch signal (see Appendix III). A low-pass, recursive 4th order Butterworth digital filter was used to eliminate frequencies greater than 35 Hz in the twitch before differentiation. Normalized (for twitch amplitude, expressed as %Pt/ms) rates of change in the signal were also calculated as R+dP/dt, R-dP/dt, and RdP/dta, for peak positive, peak negative and average positive dP/dt, respectively. The same procedures were also applied to the potentiated twitches (Pt+). Absolute and normalized (per MBCSA) peak force values were determined for the three tetanic frequencies and the MVC record (see Appendix III). Ratios of tetanic forces (10Hz to 70Hz and 20Hz to 70Hz) were also determined. From the two minute fatigue test a fatigue index (FI) was calculated as the ratio of the lowest peak force (in the last 10 seconds) to the highest peak force (in the first 10 seconds) (see Appendix III).

5.3 RESULTS

Subject participation in the study averaged 2.7 ± 0.14 sessions per week throughout the 24 week period, for a total of 64.5 ± 5.8 training sessions. The age, height and weight of the two groups were not significantly ($p \leq 0.05$) different, and height and weight did not change in either group over the course of the study (Table 14). Muscle plus bone cross-sectional area (MBCSA) was significantly increased by nearly 8.5%, in the experimental group (Table 14), and did not change in the control group over 24 weeks (+2.3%). The change in the experimental group MBCSA was significant at 12 weeks (5%) and at 24 weeks (a further 3.5%). The lifestyle and activity pattern of the control group did not change substantially over a 24 week period.

The experimental group demonstrated significant increases in both dynamic (1RM)(~ 30%) and static strength (MVC) (~ 21%) over the 24 week period (Tables 14 and 15). The improvement in MVC was approximately ~ 10% in each 12 week period (Fig. 7). Normalized MVC (RMVC) was significantly increased at 24 weeks (12.6%) but not at 12 weeks (5.1%) in the experimental group (Fig. 7). In the control group, MVC strength was unchanged (-2.6%) between 0 and 24 weeks. The RMVC over 24 weeks was also not significantly changed (-4.5%). There was no significant change in the FI in either group at 12 or 24 weeks (Table 15).

2 OF/DE 2

TABLE 14. Physical, Anthropometric and Performance Characteristics

		Age (y)	Height (cm)	Weight (kg)	1RM (kg)	mBCSA (cm^2)
Exercise group (n=13)	Pre	70.9±4.2 (64-78)	175.1±6.6	79.1±11.7	9.8±1.9	51.8±10.5
	Post	71.2±4.2	175.2±6.6	79.0±11.4	12.7±2.3*	56.2±12.3*
Control group (n=8)	Pre	71.0±3.9 (65-78)	177.9±4.1	78.9±7.6	-	52.9± 7.6
	Post	71.5±3.8	177.8±4.0	79.4±7.3	-	54.1± 7.2

Values are means ±SD and age range in brackets. Pre is 0 weeks and post 24 weeks of training. MBCSA is muscle plus bone cross-sectional area at the mid-arm level. 1 RM is 1 maximum repetition using pulley weights. * denotes significant difference ($p<0.02$) between week 0 and week 24.

Table 15. Comparison of Maximal Voluntary Forces and Index of Fatigue

		MVC (Nm)	RMVC (Nm/cm^2)	FI
Exercise group (n=13)	Pre	41.04 ±8.7	0.79 ±0.11	0.452 ±0.13
	Post	49.72[a] ±12.4	0.89[b] ±0.14	0.451 ±0.11
Control group (n=8)	Pre	47.00 ±7.8	0.88 ±0.10	0.410 ±0.13
	Post	45.78 ±9.0	0.84 ±0.14	0.417 ±0.14

Values are means ±SD. Pre is 0 weeks and post is 24 weeks of training. MVC is maximal voluntary contraction and RMVC is MVC normalized for muscle plus bone cross-sectional area. FI is fatigue index. [a] and [b] denote significant differences (p=0.001 and p=0.017, respectively) between week 0 and week 24.

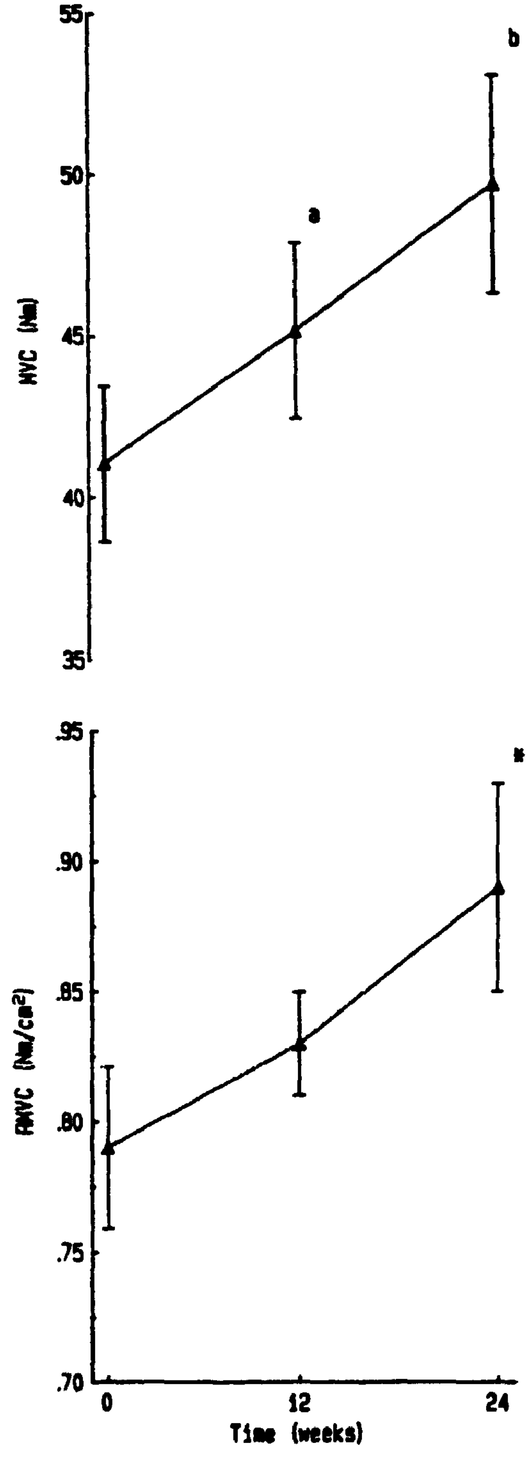

Fig. 7 Changes in voluntary contractions (MVC) (top panel), and normalized MVC (RMVC) per fat-corrected muscle plus bone cross-sectional area (MBCSA) (lower panel) in the experimental group. Values are mean ± SE. a = significant difference ($p \leq 0.05$) between 0 and 12 weeks, and b = significant difference between 12 and 24 weeks. * = significant difference between 0 and 24 weeks.

Table 16 is a summary of the twitch and post-activation twitch parameters. Significant changes over 24 weeks occurred in the experimental group. Twitch TPT increased 8.1% and RdP/dta decreased 8.7% The greater portion of these changes occurred in the first 12 weeks with TPT increased by 5.5% and RdP/dta decreased by 6.7% (Fig. 8). There was no effect on post-activation twitch parameters as a result of 24 weeks of training. In both groups, at pre- and post- tests post-activation twitch torques were significantly potentiated (~ 145%) compared with unpotentiated twitches. Absolute rate of force development was significantly greater than non-potentiated twitches by approximately 130%.

Tetanus parameters are summarized in Table 17. Absolute tetanic tension increased significantly at all 3 frequencies in the experimental group by 32% to 39% compared to non-significant changes in the control group of 9% (70Hz) to 20% (10Hz). For the experimental group, slightly more than half (~ 19%) of the increase for the three frequencies occurred during the first 12 weeks (Fig. 9). Normalized tetanic tensions also increased in the experimental group at all 3 frequencies (23% to 30%), evenly divided between the first and second 12 week periods (Fig. 9). There were no significant differences in the two tetanic ratios in either group consequent to the 24 week training.

TABLE 16. Comparison of Twitch and Post-activation Twitch Parameters

A. Twitch

		Pt (Nm)	TPT (ms)	½RT (ms)	dP/dta (Nm/ms)	+dP/dt (Nm/ms)	-dP/dt (Nm/ms)	RdP/dta (%PT/ms)	R+dP/dt (%Pt/ms)	R-dP/dt (%Pt/ms)
Exercise group (n=13)	Pre	4.3	81.6	86.9	0.065	0.129	-0.045	1.49	3.01	-1.02
		±1.6	±7.6	±19.9	±0.03	±0.05	±0.02	±0.13	±0.58	±0.28
	Post	4.4	88.2[a]	87.7	0.060	0.126	-0.046	1.36[b]	2.83	-1.03
		±1.7	±5.5	±19.2	±0.02	±0.05	±0.02	±0.08	±0.64	±0.26
Control group (n=8)	Pre	3.8	82.4	83.5	0.057	0.114	-0.044	1.48	2.99	-1.08
		±1.1	±7.7	±23.9	±0.02	±0.04	±0.02	±0.17	±0.42	±0.34
	Post	4.0	82.5	83.2	0.06	0.121	-0.046	1.47	2.83	-1.08
		±1.2	±6.6	±15.3	±0.03	±0.08	±0.03	±0.12	±0.73	±0.25

B. Post-activation twitch

		Pt (Nm)	TPT (ms)	½RT (ms)	dP/dta (Nm/ms)	+dP/dt (Nm/ms)	-dP/dt (Nm/ms)	RdP/dta (%PT/ms)	R+dP/dt (%Pt/ms)	R-dP/dt (%Pt/ms)
Exercise group (n=13)	Pre	10.2	80.8	73.0	0.154	0.282	-0.118	1.51	2.76	-1.14
		±2.8	±6.8	±15.4	±0.05	±0.09	±0.05	±0.10	±0.47	±0.30
	Post	10.9	81.3	72.3	0.161	0.289	-0.121	1.48	2.68	-1.11
		±2.5	±4.4	±12.7	±0.04	±0.06	±0.03	±0.08	±0.28	±0.16
Control group (n=8)	Pre	9.3	81.9	66.8	0.138	0.254	-0.118	1.48	2.67	-1.29
		±2.0	±7.6	±12.5	±0.04	±0.10	±0.02	±0.11	±0.43	±0.22
	Post	9.8	81.7	69.2	0.148	0.286	-0.118	1.49	2.88	-1.21
		±2.8	±6.5	±10.7	±0.05	±0.12	±0.03	±0.11	±0.45	±0.11

Values are means ±SD. Pre is 0 weeks and post 24 weeks of training. [a] and [b] denote significant difference ($p=0.008$ and $p=0.003$, respectively) between week 0 and week 24. Pt is supramaximal twitch tension, TPT is time to peak tension, ½RT is one-half relaxation time, d/Pdta is average rate of twitch force development, +dP/dt is maximum rate of twitch force development, -dP/dt is maximum rate of twitch force decline, R denotes normalized values for the above twitch rates.

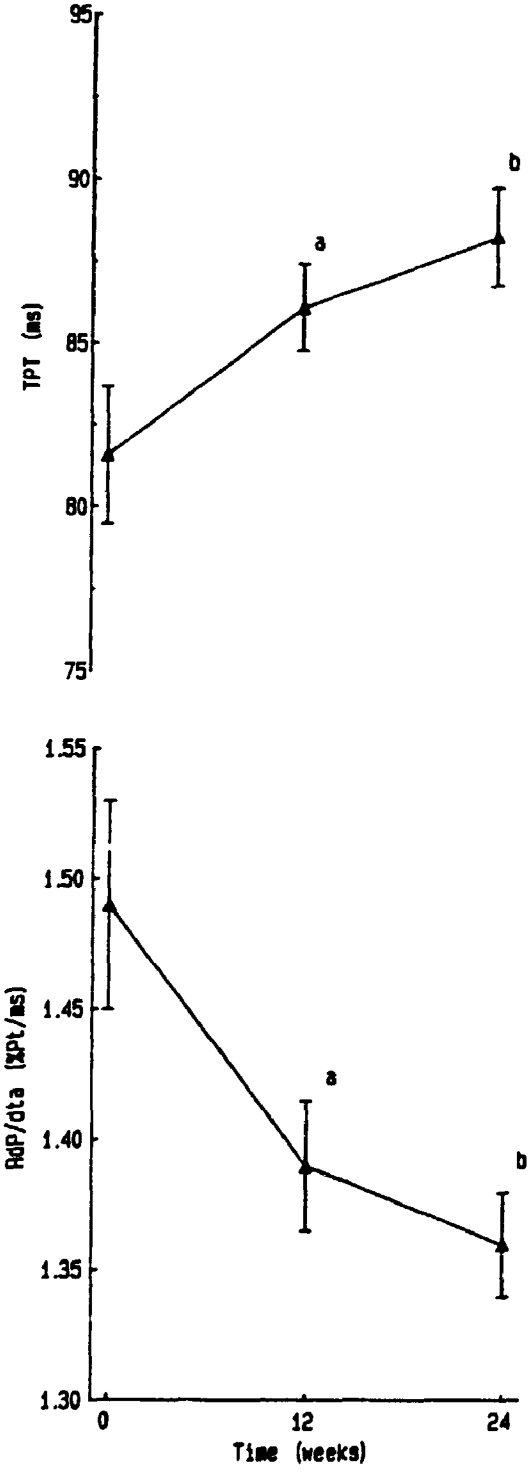

Fig. 8 Change in twitch parameters in the experimental group during the training program. Top panel illustrates change in time-to-peak torque (TPT). Lower panel is the normalized average rate of torque development (RdP/dta). Values are mean ± SE. a = significant difference ($p \leq 0.05$) between 0 and 12 weeks, and b = a significant difference between 12 and 24 weeks.

Table 17. Comparison of Tetanic Parameters

		10Hz (Nm)	20Hz (Nm)	70Hz (Nm)	R10Hz (Nm/cm^2)	R20Hz (Nm/cm^2)	R70Hz (Nm/cm^2)	10/70Hz	20/70Hz
Exercise group (n=13)	Pre	5.8 ±1.2	10.1 ±3.0	13.3 ±4.9	0.117 ±0.04	0.202 ±0.07	0.265 ±0.12	0.50 ±0.21	0.78 ±0.09
	Post	8.0* ±1.9	13.4* ±3.7	18.5* ±5.6	0.150* ±0.05	0.249* ±0.08	0.344* ±0.01	0.46 ±0.18	0.73 0.12
Control group (n=8)	Pre	4.5 ±1.6	10.8 ±2.9	14.5 ±4.7	0.08 ±0.03	0.200 ±0.05	0.270 ±0.08	0.35 ±0.18	0.76 ±0.09
	Post	5.4 ±2.3	11.7 ±3.1	15.7 ±4.1	0.09 ±0.04	0.210 ±0.04	0.290 ±0.05	0.35 ±0.16	0.75 ±0.10

Values are means ±SD. Pre is 0 weeks and post is 24 weeks of training. 10Hz, 20Hz and 70Hz are tetanic torque from three frequencies of stimulation. R denotes tetanic torque normalized for muscle plus bone cross-sectional area of the arm. 10/70Hz and 20/70Hz are ratios of tetanic forces at the indicated frequencies. * denotes a significant difference ($p \leq 0.01$) between week 0 and week 24.

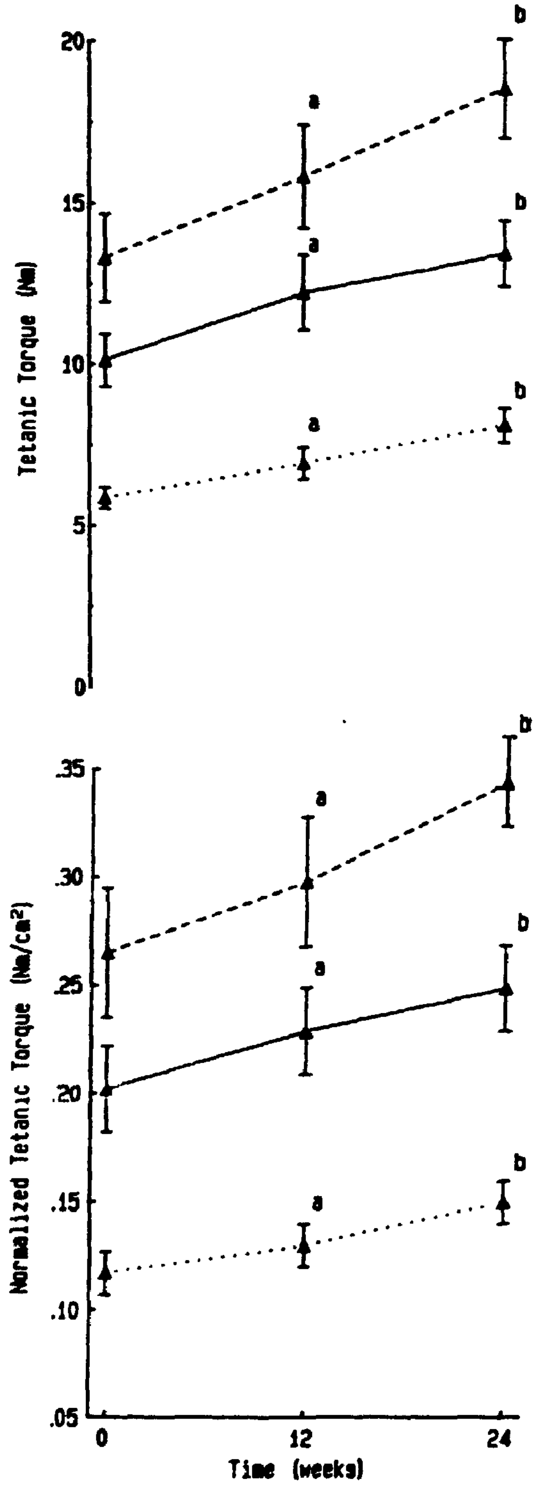

Fig. 9 Change in tetanic parameters at 3 frequencies in the experimental group during the training program. Top panel illustrates the change in absolute tetanic torque. Lower panel is the change in normalized tetanic torque (per MBCSA). 10Hz (....), 20Hz (____), and 70Hz (----). Values are mean $\pm$ SE. a = significant difference ($p \leq 0.05$) between 0 and 12 weeks, and b = significant difference between 12 and 24 weeks.

5.4 DISCUSSION

5.4.1 Strength Gains

The results of this study have demonstrated that a strength training program can improve the performance of skeletal muscle in aged subjects. The relative increase in voluntary strength (~ 25%) is similar to reports on younger subjects (Dons et al., 1979; Kaufman, 1985; Rutherford et al., 1986). Of the few strength training studies reported on aged individuals, durations of between 6 and 12 weeks have been most common (Aniansson et al., 1980; Moritani and deVries, 1980; Kaufman, 1985; Frontera et al., 1988), except for the 10 month study of Aniansson, et al. (1984) and a 6 month study of Agre, et al. (1988). Strength has been measured using a variety of techniques (MVC, 1RM, isokinetic machines), in different muscle groups, and the reported improvements in aged subjects therefore span a wide interval from 8% to over 200%, although the most frequently cited interval has been 10% to 20% (Aniansson et al., 1980; Moritani and deVries, 1980; Aniansson et al., 1984; Kaufman, 1985; Frontera et al., 1988). In the present study, the MVC showed an increase of 10% in the first 12 weeks, and a further increase of 10% in the next 12 weeks, and a 24 week change in 1RM of 30%. These results are similar to the magnitude of change in the various voluntary performance measures cited above. It is often reported in younger subjects that dynamic training does not result in improvements in MVC, or they are minimal compared with changes in 1RM (Sale, 1986). This specificity was not found in the present study which may suggest that skeletal muscle in aged subjects represents an hypokinetic muscle which with training shows a more overall and less specific improvement in strength.

5.4.2 Tetanus Parameters

This is the first study of aged subjects that has measured evoked contractile properties during a relatively long term strength training program. Tetanic torque (at 70Hz) increased 18.5% over the first 12 weeks and a further 17.5% over the subsequent 12 weeks. This change in the experimental group may be slightly over-estimated since there was also a non-significant increase in the 70Hz tetanic torque of 9% in the control group between 0 and 24 weeks. This is probably the result of the subjects being better able to relax and not resist the contraction during the test. Nevertheless, the change in tetanic torque in the experimental group was significant and an important result.

Results from other human studies which have used electrically evoked measures of tetanic responses following training have been contradictory. McDonagh, et al. (1983), Davies, et al. (1985), and Young, et al. (1985) reported no change in fused tetanic forces following 5 to 8 weeks of isometric training of the elbow flexors, plantar flexors and first dorsal interossei. Using the adductor pollicis muscle, however, Duchateau and Hainaut (1984a, 1984b, 1988) have shown an 10% to 20% improvement in tetanic force following 6 and 12 weeks of isotonic training, and Hainaut, et al. (1981) and Duchateau and Hainaut (1984b) have shown a ~ 20% increase in tetanic force following 12 weeks of isometric training in this muscle. Unless the adductor pollicis is an especially 'trainable' muscle, the differences in these findings can only be attributed to differences in methods or the subject population. The subject numbers in the various studies of Duchateau and Hainaut ranged from 8 to 20 compared with 2 (McDonagh et al., 1983), 7 (Davies et al., 1985), and 4 (Young et al., 1985) subjects. In the two studies with 4 and 7 subjects, there is a general trend, although not statistically significant, of an increase in tetanic tension of 4% to 9%. Interestingly, the 9% increase was found in the hand muscle and the 4% increase in the chronically active triceps surae.

Neural changes, such as increase in maximal EMG and motor unit synchronization, and "cross-training" effects, in response to weight training are well documented (for reviews see Komi, 1986, and Sale, 1987) and are generally believed to be the major factor contributing to strength increases measured within the first 10 weeks, and more especially in older individuals (Moritani and deVries, 1980). Many of these studies have cited the large increase in voluntary strength compared with slight or no change in muscle CSA as the basis for their conclusions (Ikai and Fukunaga, 1970; Dons et al., 1979; Moritani and deVries, 1979). More recent studies have suggested, however, that with better measures of muscle CSA and density using CT scans there are changes within the muscle that can account for some of the improvements in strength during the first 12 weeks of training (Young et al., 1983; Jones and Rutherford, 1987; Frontera et al., 1988). The increase in tetanic torques (particulary a fused tetanus) after 12 weeks of training in this study substantiates these suggestions since electrical stimulation by-passes the central neural mechanisms and only the peripheral muscle properties were measured.

Some of the lower frequency (10Hz and 20Hz) tetanic torque increases found in this study may be also partly related to the increase in TPT. The increased time course of the twitch provides the opportunity for greater summation to occur, particularly during unfused tetani.

5.4.3 Force and Cross-sectional Area

In the first 12 weeks of the present study MBCSA increased 5% and 70Hz tetanic torque increased approximately 18.5%, thus leaving about 13.5% of the improvement in torque unaccounted for by gross hypertrophy, and therefore resulting in an increase in normalized tension. Although it has been shown that MBCSA may not accurately reflect actual muscle CSA

(Young et al., 1983), particularly in aged individuals (see Chapter Four), the 5% increase in MBCSA is similar to reports of muscle CSA changes found using CT scans in other studies of a similar duration in both young and aged subjects (Young et al., 1983; Jones and Rutherford, 1987; Schmidtbleicher and Buehrle, 1987; Frontera et al., 1988). The increased CT scan density measurements reported in these other studies after training suggest several possibilities which may account for the further discrepancy that is found between strength and CSA even when muscle CSA is accurately measured. Among them are increased myofilament density, decreased fat content within the muscle, and increased proportion of connective tissue (Horber et al., 1985; Jones and Rutherford, 1987). Enoka (1988) has suggested that changes in any of these factors, but particularly in the quantity or quality of connective tissue, would result in an increased specific (normalized) tension.

An alternate hypothesis must also be borne in mind when interpreting changes in specific (normalized) tension. Although CT scans permit an accurate assesement of muscle CSA it is known that the measure of PCSA is more correct for normalizing muscle forces (Maughan, 1984; Edgerton, 1986). With hypertrophy the pinnation angle of the fibres attached to the tendon is increased and there may also be changes in fibre length. Both of these factors potentially cause a greater increase in PCSA compared with anatomical CSA (Gans, 1982; Powell et al., 1984; Woittiez et al., 1984). If accurate measures of PCSA can be estimated *in vivo* (Rice et al., 1988) it may be possible to more completely account for changes in muscle force. This is exemplified in a compensatory overload study of rat hindlimb muscles in which a 30% increase in tetanic force was completely accounted for by a 30% increase in PCSA resulting in no change in specific tension (Roy et al., 1985). Clearly, further research is needed in the area of human muscle morphology and changes associated with hypertrophy and atrophy.

Although it is generally believed that gross muscle hypertrophy becomes a significant factor only after 12 to 16 weeks of strength training (Komi, 1986), in the second 12 weeks of this study a greater rate of hypertrophy was not evident using the MBCSA measurement. MBCSA increased only 3.5% more, but the 70Hz tetanic torque increased another 17% Some of this further change in tetanic torque might be attributed to an habituation factor (see previous discussion), but most of the discrepancy is probably either related to the MBCSA measurement not reflecting the actual muscle CSA or PCSA change, or a further result of continuing adaptations in the muscle and connective tissue composition discussed previously. The number of strength training studies undertaken for more than 16 to 20 weeks is very limited, and to date none have looked at CT muscle area or density changes. Studies reported by MacDougall (1986) of up to 6 months of training in younger adult triceps brachii have shown increases in both Type I and Type II fibre sizes resulting from increased numbers of myofilaments within the myofibrils. No strength studies in aged individuals have been reported beyond 12 weeks of training.

5.4.4 Twitch Parameters

Significant changes in the twitch parameters were a lengthening of TPT and a decrease in the RdP/dta, both at 12 and 24 weeks. Cross-sectional studies on younger subjects, comparing weight-lifters and normals have reported similar findings of a longer TPT in strength athletes (Sale et al., 1983; Alway et al., 1988), but longitudinal training studies of young subjects have reported no change (McDonagh et al., 1983; Davies et al., 1985; Young et al., 1985), or decreases in this parameter (Schmidtbleicher and Haralambie, 1981; Duchateau and Hainaut, 1984, 1988). One of the longitudinal studies was carried out for 12 weeks (Duchateau and Hainaut, 1984), but the remainder were less than 8 weeks in duration. The longitudinal studies of Duchateu and Hainaut (1984, 1988) also reported increases in Pt following training, but Pt did not change in this study or in the other studies cited above. The short durations of training in the longitudinal studies contrasted to the many years of weight training in the cross-sectional studies suggest that in younger subjects longer periods of training are required to determine if similar changes will be evident in these parameters.

Support from animal experimentation for slower twitch characteristics and no change in Pt following strength training is equivocal. Six months of low to moderate level strength training in non-human primates produced no change in TPT or Pt (Edgerton, 1976), but moderate to high level weight training in cats resulted in longer twitch times (Gonyea and Bond-Petersen, 1978). Compensatory hypertrophy models have also given inconsistent results (Roy et al., 1982; Roy et al., 1985; Gollvik et al., 1986). The suitability of these compensatory models to represent strength training overload is questionable (Edstrom and Grimby, 1986) and therefore comparisons with human studies may not be warranted. No strength training studies using aged animals have been reported.

The mechanisms responsible for slowed twitch parameters could be related to changes in excitation-contraction coupling processes, or to morphological changes in the muscle or connective tissue. Slowed excitation-contraction coupling of the twitch may involve Ca^{2+} kinetics related to sarcoplasmic reticulum (SR) volume, or changes in myosin ATP'ase activity. However, in the study by Gonyea and Bond-Petersen (1978) the prolonged twitch contraction times consequent to weight-lifting in cats occurred without any change in myosin ATP'ase activity, and in the study by Alway, et al. (1988) alterations in the SR volume to myofibrillar ratio were not different between the weight-lifters and control subjects. Also, relaxation of the twitch was not significantly prolonged in this study which may suggest no change in calcium uptake kinetics following strength training, as it has been shown that relaxation rate is particularly related to SR properties (Kugelberg and Thornell, 1983; Klug and Tibbits, 1988).

Further to the above discussion, the present study found no impairment of twitch potentiation parameters after strength training which may suggest no change in the excitation-contraction coupling processes. Twitch potentiation is considered to be a measure of the intensity of activation and is usually observed in fast twitch muscles by an increase in the rate of force development and Pt+ without changes in contraction time following a brief period of tetanic stimulation (Burke, 1981; MacIntosh and Gardiner, 1986). Similar findings have also been reported by Vandervoort, et al. (1983) following 5 to 10 seconds of voluntary contraction used to induce potentiation. Using this method, the aged subjects showed the usual potentiation responses with about a 60% potentiation in Pt+ and +dP/dt with no change in TPT. It should be realized, however, that other mechanisms which pertain to muscle stiffness and spindle activity may also be responsible for twitch potentiation (Suzuki et al., 1988).

Morphological changes following overload of skeletal muscle include muscle hypertrophy and increase in collagen synthesis (Booth and Gould, 1975). As reported by MacDougall (1986), the proportion of connective tissue to muscle fibres is the same between weight-lifters possessing very large muscles, and controls. Based on compensatory hypertrophy in rats (Binkhorst and van't Hof, 1973), and on human cross-sectional comparisons of weight-lifters and controls (Alway et al., 1988) it has been suggested that muscle hypertrophy would not be solely responsible for alterations in the twitch time course. It is known, however, that with ageing connective tissue becomes less compliant (Viidik, 1982; Beyer, 1983; Vailas et al., 1985) and it has been suggested that with exercise connective tissue becomes more compliant in both young and old (Booth and Gould, 1975; Beyer, 1983). Another component of muscle stiffness resides in the myofilaments and cross-bridges during contraction (Ford et al., 1981; Stein and Gordon, 1986), and it has been reported by Less, et al. (1977) that this aspect of muscle stiffness is more extensible after training. The increased time course and slowed rate of twitch development found in this study could therefore be explained by an increase in muscle compliance in aged subjects after strength training. This response may be enhanced in this population due to a less compliant muscle before training compared with younger subjects. However, the work in this area is very limited, especially concerning the connective tissue response to strength training (Tipton et al., 1987; Stone, 1988).

Sale, et al. (1982) suggested that muscle extensibility could be reflected in the twitch-to-tetanus ratio and that a decrease in the ratio would imply increased extensibility. The ratio (70Hz) in this study decreased from 0.32 to 0.24. A decrease in stiffness would probably also attenuate any increase in twitch tension which has been shown to occur in younger subjects (Sale et al., 1983; Duchateau and Hainaut, 1984a) after strength training. Rack and Westbury (1984) have shown that the elastic properties of the muscle are more compliant at low forces but during higher forces (presumably tetanus) the increased stiffnes is equally affected by both muscle and tendon properties. Although it is usually assumed that slowed contractile twitch properties accompanying ageing are due to alterations in the Ca^{2+} regulatory system (Vandervoort and McComas, 1986), the present results appear to suggest that this system does not adapt with strength training in aged subjects. Alternatively, the suggested structural changes have masked changes in excitation-contraction coupling parameters which may have occurred. Further studies on the aged are required to examine the effects of strength training on both the biochemical and structural properties associated with contraction.

5.4.5 Summary

Using both voluntary and electrically evoked measures this study has demonstrated that, contrary to many previous reports on aged subjects, some of the improvement in strength could be attributed to changes within the muscle, or its supporting connective tissue structures. Compared with the controls, the aged individuals in this study had significant improvements in MVC and tetanic torques at 12 and 24 weeks post-strength training, and a significant increase in 1RM at 24 weeks. Upper arm MBCSA's were also increased which suggests muscle hypertrophy, but to a lesser extent than the improvements in strength. This resulted in an increase in specific torques for both MVC and tetanus. Twitch contractions were slower due to longer TPT's and smaller RdP/dta's, but there was no difference in 1/2 RT or Pt. There were no changes in the FI nor in Pt+ parameters. These results suggest that skeletal muscle strength of aged subjects is adaptable at a similar rate as in younger subjects. Not all of the increase in strength can be attributed to neural changes, but must include changes in the structure and size of the muscle, and possibly more importantly and specifically in the mechanisms that govern the elastic properties of the muscle-tendon complex. The model chosen may represent a very untrained muscle which can therefore demonstrate changes in contractile function following a relatively moderate duration of overload that previously has been seen only in cross-sectional studies on younger individuals.

CHAPTER SIX

GENERAL SUMMARY AND IMPLICATIONS

The first study provided voluntary strength results for five upper-limb and four lower-limb muscle groups from 37 males (average age of 79 y) and 81 females (average age 77 y). Although the measurement method used was semi-quantitative, the results were within the range reported by other studies using more sophisticated measuring devices. However, there are few results available for comparison for many of the muscle groups on subjects over 75 years of age.

Males were stronger than females on an absolute, but not a relative (per kg body weight) basis. From the slopes of the regression equations, losses in strength between 62 and 102 years of age were between 1.5% and 3.5% depending on the sex and muscle group. Compared with about 30 years of age, 20% of maximum strength is lost by 75 years of age (Vandervoort et al., 1986). If strength declines at an average rate of 2.5% per year for the next 25 years a person will have lost 62.5% of the remaining 80%, resulting in a total reduction of 70% by age 100. This value is similar to the 50% loss by age 90 reported by Vandervoort, et al. (1986).

The regression analysis determined that age was the most significant factor in explaining the decline in strength and weight was secondary and significant for most female muscle groups. The strength scales presented in Chapter Two allow aged individuals to be quickly categorized or screened for weakness from a simple MS measurement and knowledge of age and weight. The technique is also qualitatively useful for monitoring strength changes in response to exercise or rehabilitative programs.

The study determined that the MS is limited in its range for testing relatively younger (< 75y) and vigorous subjects and that certain muscle groups with short lever arms (plantar flexors) could not be satisfactorily measured. The strong relationship between strength and age suggests that age should be considered and adjusted when comparing voluntary strength between individuals in this older elderly age range. This is analogous to strength comparisons between younger individuals in which muscle size is the most significant factor to adjust.

The CT study revealed a remarkable reduction in limb muscle tissue compared with younger subjects, particularly in the leg. It remains to be determined whether this reduction in muscle tissue, not previously quantified, will account for the age-related decline in voluntary strength. According to Vandervoort and McComas (1986), aged subjects, for the most part, are not limited by central neural drive.

The plantar flexor group was more affected by replacement of muscle with NMT than the upper limb muscles. On the other hand, the upper limb muscles seemed more susceptible to gross atrophy in the aged with greater amounts of subcutaneous tissue present. Whether this implies an upper to lower limb ageing difference, or simply represents differences in muscle group and limb anatomy which are not specific to upper or lower location, remains for further studies to determine using other muscle groups. It was qualitatively apparent that the limb muscles of the 65 to 70 year old subjects more closely resembled, in size and composition, those of the younger group than those of subjects over 75 years of age. This observation lends support to the concept that muscle functional changes are not significant until beyond 70 years of age.

Multiple CT imaging proved to be a useful method for obtaining in vivo estimates of muscle group PCSA. The regression equations have provided a means of estimating muscle volume, with little error, from a single CT scan. These procedures should be applied to other muscle groups and on a larger sample to substantiate the technique. Perhaps a multiple imaging and cadaver investigation should also be performed to better determine the validity and limitations of the method.

The comparison between CT and AP in Chapter Four identified certain limitations for the use of AP to determine limb muscle size in an aged population. There was no surface measure which demonstrated any relationship to the significant amount of NMT located in muscle of aged individuals, and therefore prediction equations for a particular muscle group size are not attainable or have error ranges of more than 10%. Perhaps with more subjects and with more AP measurements stronger equations could be derived. The study is the first, however, to validate the use of AP methods for limb composition determination in aged subjects, and has provided improved, and age-specific equations for several commonly used measurements.

Although aged individuals are weaker and have reduced muscle mass, the final study demonstrated that they respond, on a relative basis, like younger adults to a muscle strengthening exercise program. The electrically evoked techniques used allowed the peripheral muscle to be measured without central neural interference. Thus, evidence was provided that muscle in aged subjects also responds to strength exercises, contrary to the suggestion by Moritani and deVries (1980) that strength was improved in aged subjects only as a result of changes in neural mechanisms.

Muscle and muscle force are integrated into a system of, on the one side, neural controlling mechanisms, and on the other side, structural modifiers. The expression of muscle strength in humans _in vivo_ is therefore only partly a reflection of the contractile process of a particular muscle. The results of the final study suggested that some of the contractile changes could be a result of changes in the quality or quantity of structural force modifiers (i.e., stiffness properties), as well as quantitative and architectural changes of the muscle tissue per se. Most previous studies, usually with younger adults, have concentrated on the response of neural, or contractile mechanisms in response to exercise. Aged individuals may be a useful model to examine these other aspects of muscle strength expression, or they may simply represent the response of a very untrained system. Certainly further studies are required before definite conclusions can be made.

From this thesis it is clear that the neuromuscular system of aged humans to date has received a limited amount of research attention. It seems that the suggestion of an accelerated decline in muscle function after 70 years of age is substantiated by the survey study reported in Chapter Two and may be partly a result of the significant change in limb muscle composition reported in Chapter Three. All is not lost, however, as the results of Chapter Five have demonstrated that the capacity for improvements in strength remains into the seventies. A small improvement in maximal voluntary force could provide a significant improvement in vigour and submaximal endurance. Strength exercises may be able to moderate the age-related decline in strength identified in Chapter Two.

APPENDIX I

Determination of Muscle Physiological Cross-sectional Area *in vivo*

Physiological cross-sectional area (PCSA) is calculated in animal muscle research by: $\frac{\text{mass(g)}}{\text{fibre length (cm)} \times 1.056 \text{ g/cm}^2}$

or more correctly as: $\frac{\text{mass(g)} \times \text{cosine of pinnation angle}}{\text{fibre length(cm)} \times 1.056 \text{ g/cm}^2}$

where 1.056 is the approximate density of muscle (Mendez and Keyes, 1960). In animal research the weight, fibre length and pinnation angle (angle at which muscle fibre joins the tendon) are directly measured. To apply this method in humans *in vivo* the mass of the muscle can be estimated from the volume calculations using the multiple imaging techniques described in Chapter Three. Mass can be derived from volume and density, as described in the chapter ($M = V \times 1.056$ g/cm^2), and from several cadaver studies the fibre lengths and pinnation angles can be obtained for the desired muscle to estimate PCSA. For many muscles the effect of pinnation angle is sometimes ignored, since the cosine value of the usual angles (5° to 25°) is close to 1. The limitation for human research is for assessing changes in fibre length and pinnation angle that could be associated with intervention studies. Currently, these are not measureable *in vivo*.

Average PCSA estimates from 13 aged males are given below and compared with the PCSA's from anthropometric estimates from _in vitro_ cadaver literature. Lean muscle group volumes were used as determined from multiple CT scans reported in Chapter Three. Not all studies listed in the table accounted for pinnation angle. There were various fibre lengths and pinnation angles reported and the results listed for the present study represent averages applied in the two formulae.

Table 18. Comparison of Physiological Cross-sectional Areas of Selected Limb Muscle Groups From Several Studies

Study	Pl. Flex.	Elb. Flex.	Elb. Exten.
Present (n=13)	268	17	45
Haxton, 1944 (n=12)[a]	127	--	--
Alexander, 1975 (n=1)[b]	191	--	--
Amis, 1979 (n=4)	--	11	47
An, 1981 (n=6)	--	12	19
Pierrynowski, 1982[c]	375	--	--
Wickiewicz, 1983 (n=3)	146	--	--
Brand, 1986 (n=1)	303	--	--
Edgerton, 1986 (n=4)	--	9	25

All values are in cm^2. a = estimated using anthropometry compared with cadavers on 6 subjects, both limbs. b = calculated by author from mass and pinnation angle estimates. c = from the literature. Others are cadaver studies and reported as an average value, or the highest value if the range was small.

Amis, et al. (1979) reported a moment arm for the triceps brachii of 2 cm to 2.2 cm at a joint angle of approximately 100^{o}. If an MVC value of 40 Nm is used for untrained aged men from Chapter Five, the specific tension calculated using a PCSA of 45 cm^2 is about 40 N/cm^2. This is similar to some of the values reported in the literature and tabulated in the paper by Edgerton (1986).

APPENDIX II

Determination of Optimal Elbow Joint Angle and Upper Stimulation Frequency for Voluntary and Evoked Contractile Properties

Seven older men (65 to 75 years of age) were assigned a random order of elbow joint angles to measure the response of the supramaximal twitch torque (Pt) and maximal voluntary contraction (MVC). It was known from preliminary testing and the literature on younger adults that the optimum angle should be approximately 90 to 100 degrees. Supramaximal twitches were first determined in this degree range and then the random order testing began at the supramaximal level (Fig. 10). MVC's were then performed in a random order (Fig. 11). These procedures were performed on two separate occasions for each subject.

On a third occasion, using the current level (milliamps.) determined from the Pt test, tetanic pulses were delivered to the muscle, in a random order of varying frequencies, for 600ms each. A force-frequency relationship was determined from these tests (Fig. 12), and 70Hz was the upper frequency limit chosen to represent a fused response for other tests described in Chapter 5.

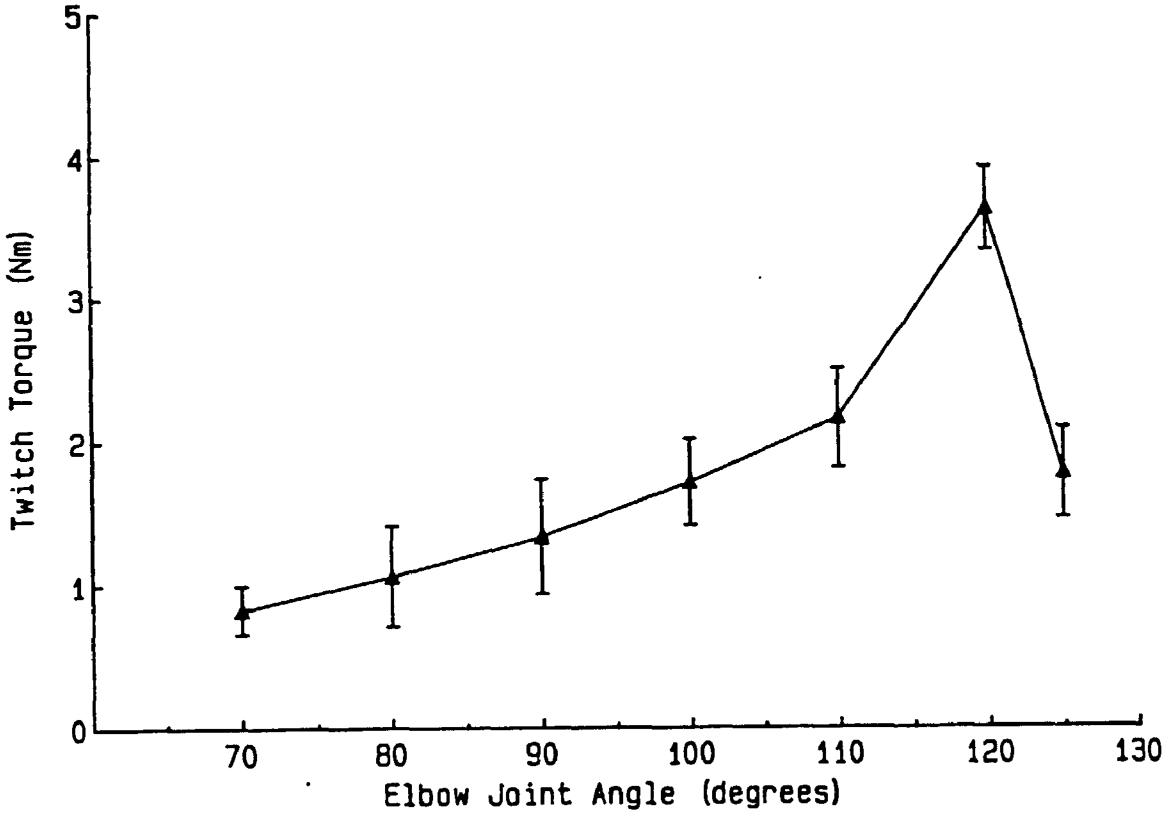

Fig. 10 Twitch torque - elbow joint angle relationship. Values are mean $\pm$ SE from 7 older men.

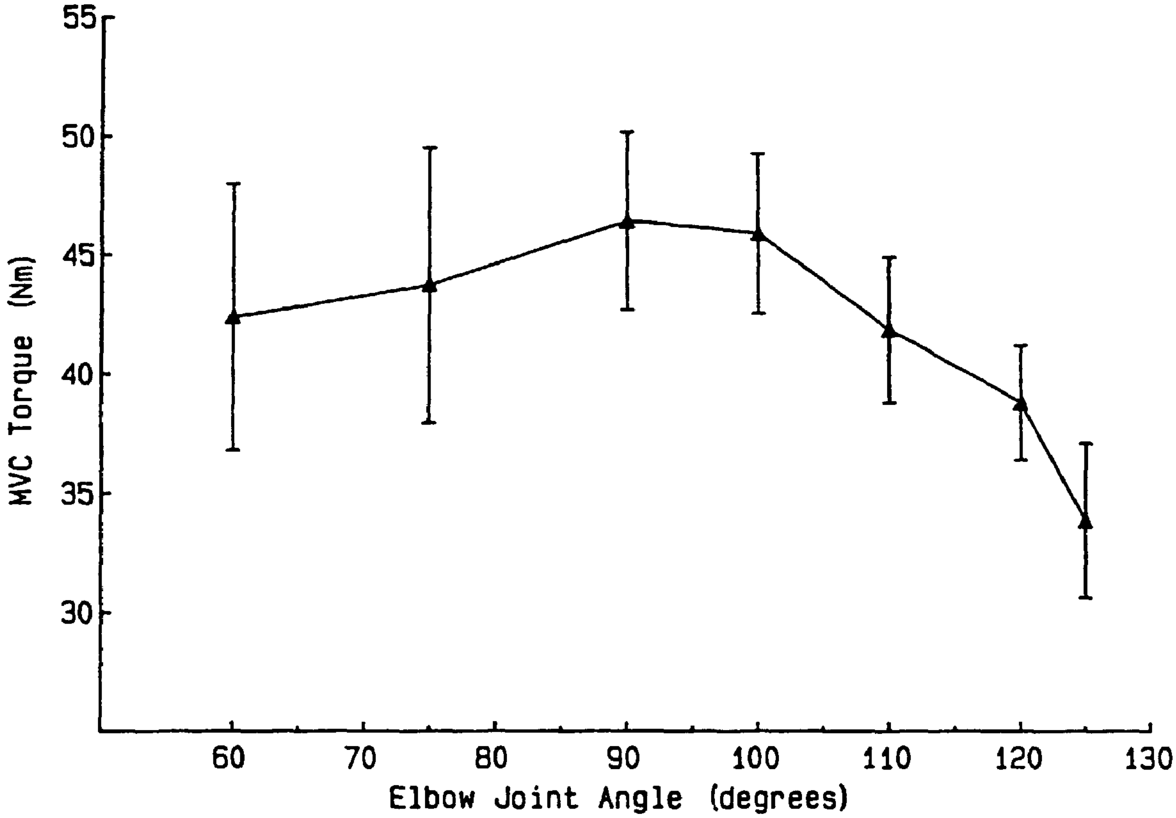

Fig 11. Maximum voluntary contraction (MVC) - elbow joint angle relationship. Values are mean ± SE from 7 older men.

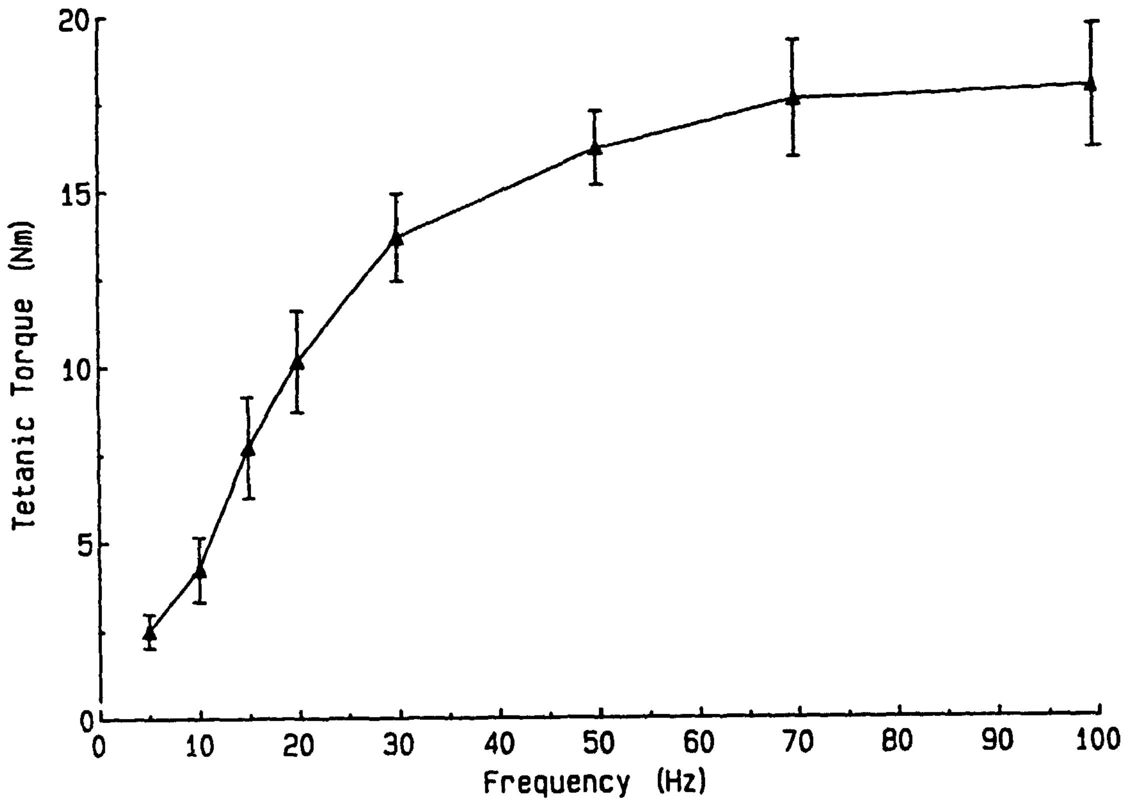

Fig 12. Force-frequency relationship for the elbow extensors. Values are mean ± SE from 7 older men.

APPENDIX III

Example Myograms of The Contractile Property Tests

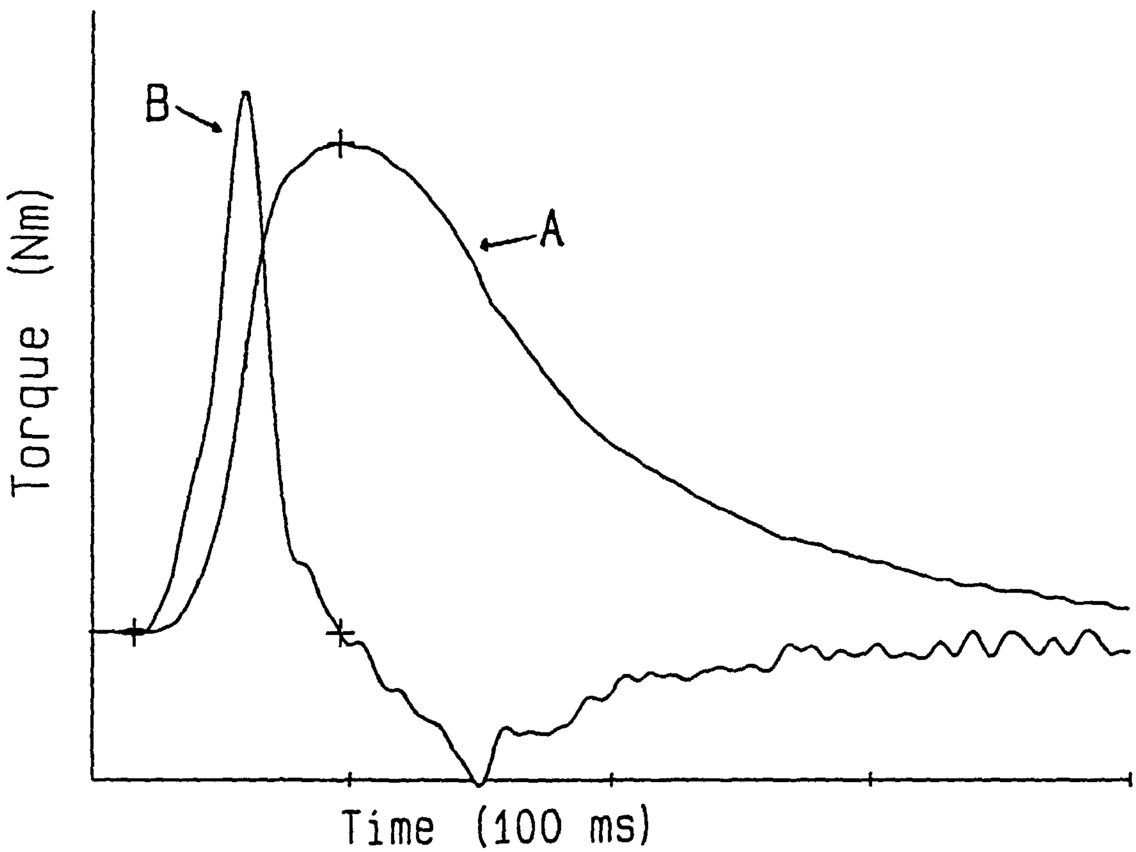

Fig. 13 Example of a supramaximal twitch myogram of the elbow extensor group. Curve A is the smoothed raw data curve, and B is the software differentiated curve. Crosses (+) indicate points chosen by computer to calculate time-to-peak tension (TPT).

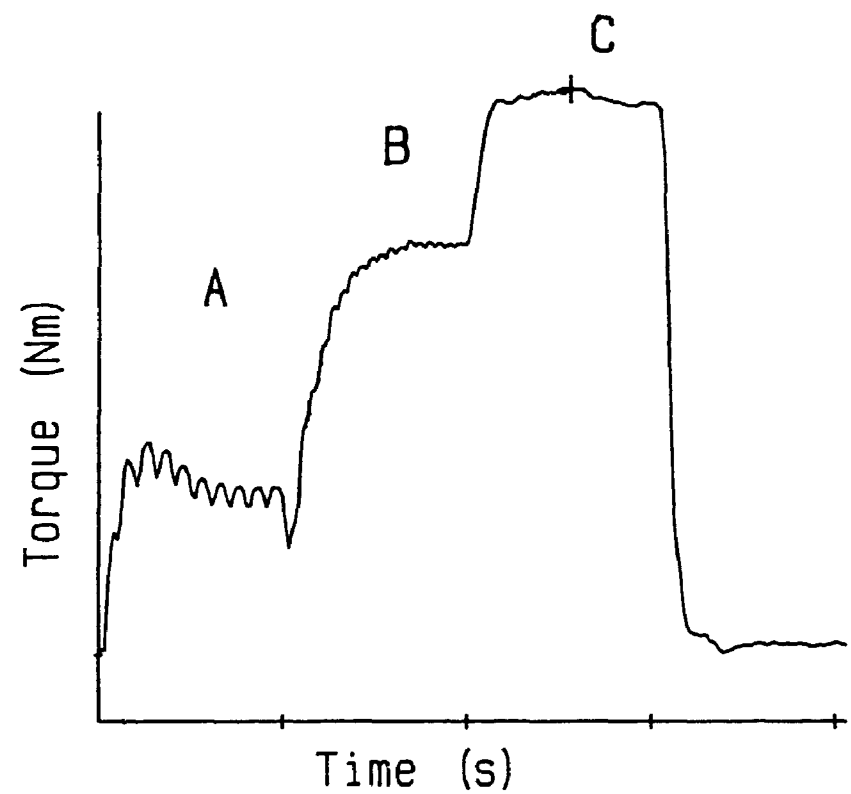

Fig. 14 Example of a maximal tetanic train myogram in the elbow extensor group. A, B, and C represent 10HZ, 20HZ, and 70HZ frequencies of stimulation, respectively. Cross (+) indicates peak 70Hz tetanic torque value chosen by the computer.

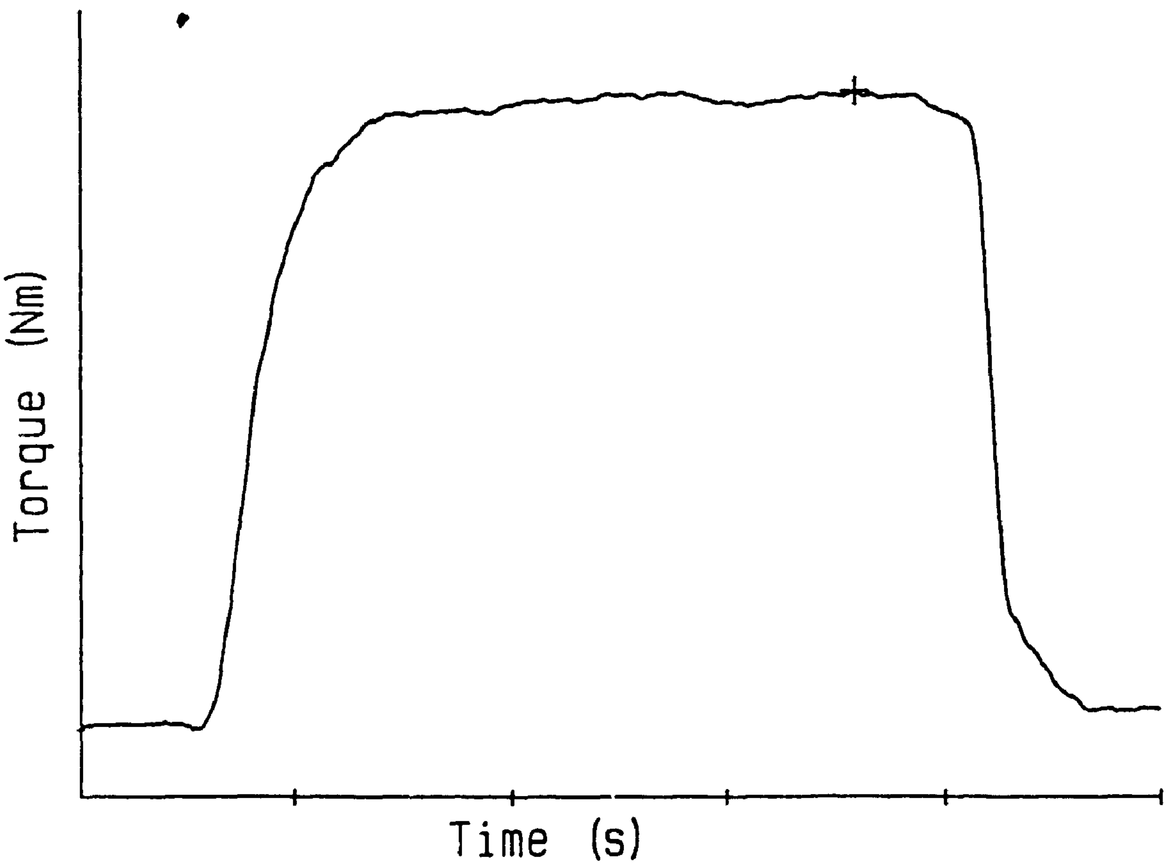

Fig. 15 Example of a maximal voluntary contraction (MVC) of the elbow extensor group. Cross (+) indicates peak torque measure chosen by computer.

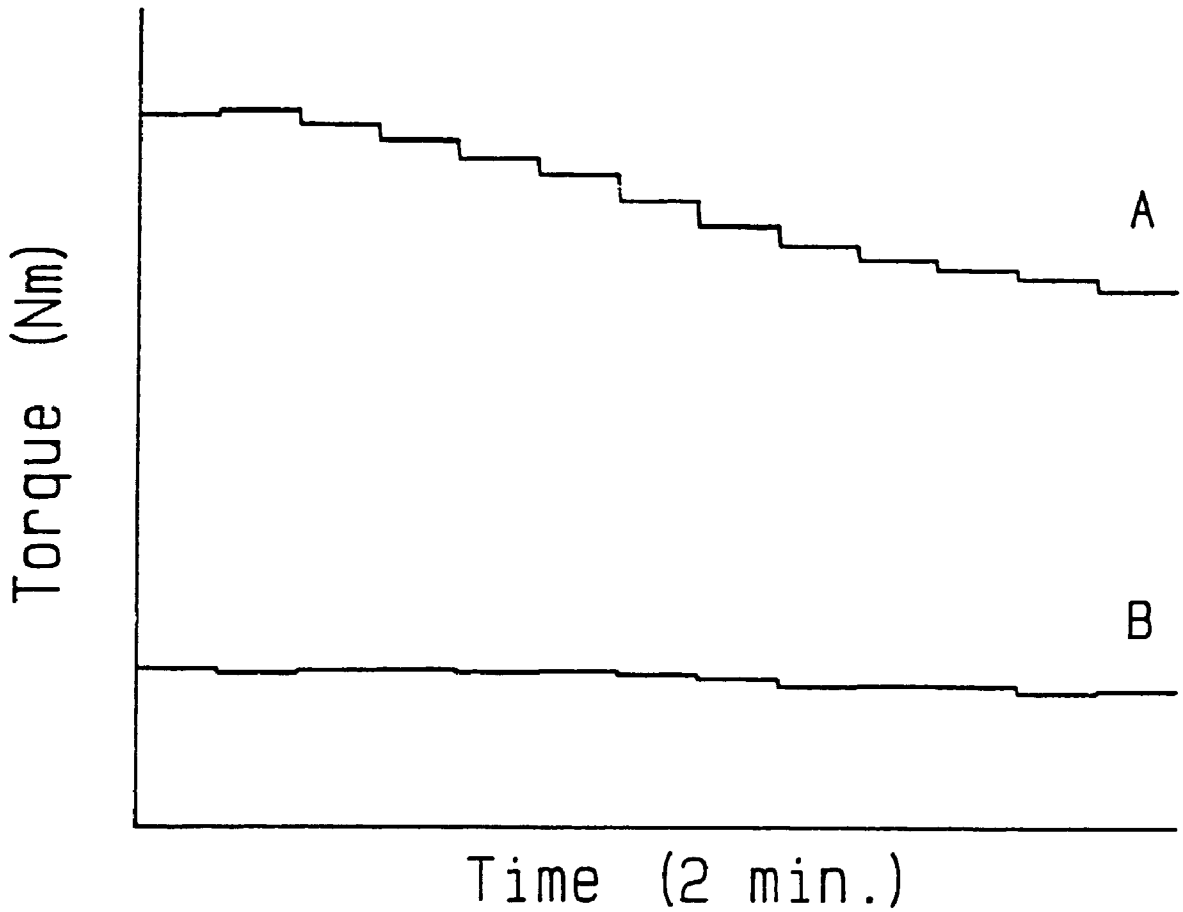

Fig. 16 Example of fatigue test response to approximately two minutes of stimulation. Trace A represents the maximum torque (displayed in 'blocks') and trace B represents the corresponding minimum or resting torque. Each block is the averaged response of approximately 9 pulses.

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